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OVERVIEW OF THE OBSERVATIONS OF SYMBIOTIC STARS

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I. INTRODUCING THE SYMBIOTIC STARS

Symbiotic stars represent a rather poor category--better to say: "collection"--of astrophysical objects. But the simultaneous presence of at least two apparently conflicting spectral features, and their peculiar light curves, have long since attracted the attention of many researchers and resulted in a large amount of observational and theoretical work. At present, this field is still very lively, and the prospects for the future are even more promising. Therefore, this monograph comes at the right time to give a *"coup d'oeil"* on what is going on in this field, in a rather untraditional way.

The term *Symbiotic Stars* commonly denotes variable stars whose optical spectra simultaneously present a *cool absorption* spectrum (typically TiO absorption bands) and emission lines of high ionization energy, such as HeII 4686 A, [OIII] 4363 A, and 5007 A, etc. Historically, it was Merrill and Humason (1932) who first called attention to the existence of a small group of stars with symbiotic spectrum: CI Cyg, RW Hya, and AX Per. The word "symbiotic" was introduced later by Merrill (1944) when describing the spectrum of BF Cyg, and this term is now currently used for the category of variable stars with composite spectrum. Figure 11-1 shows some typical optical spectra of symbiotic stars.

As illustrated in the figure, the main spectral features of these objects are: (1) the presence of a red continuum typical of a cool star, (2) the rich emission line spectrum, and (3) the UV excess, frequently with the Balmer continuum in emission. These two latter features are characteristic of the emission from a hot, low-density plasma, such as the gaseous and planetary nebulae. In addition to the peculiar spectrum, the very irregular *photometric* and *spectroscopic variability* is the major feature of the symbiotic stars, which also distinguishes them from both normal cool stars and gaseous nebulae. Moreover, the light curve is basic to identify the different phases of *activity* in a symbiotic star, as discussed in detail in the next section.

At present, 100 to 200 astrophysical objects have been classified as symbiotic (Allen 1979, 1982, 1984b; Kenyon 1986), but it is not clear whether they really represent a homogeneous group of objects. Actually, as we shall see in this chapter, there is a large variety of phenomenology that is hard to include in a coherent scheme.

Our problem is to find out the physical mechanisms that cause the symbiotic phenomenon and its variety. Probably, the same mechanisms are working with different strengths and ways in different objects. This may imply that, in some cases, one mechanism dominates over the others, and it is the one mainly responsible for the symbiotic phenomenon. Conversely, other mechanisms may be dominant in other objects. Clearly, these so far unknown mechanisms largely depend on the physical conditions that are present in symbiotic stars. A change in one basic parameter such as density or temperature makes one mechanism dominant or negligible with respect to the others.

Let us better clarify this point, which is also the basic point of this monograph series. We have observed an astronomical phenomenon character-

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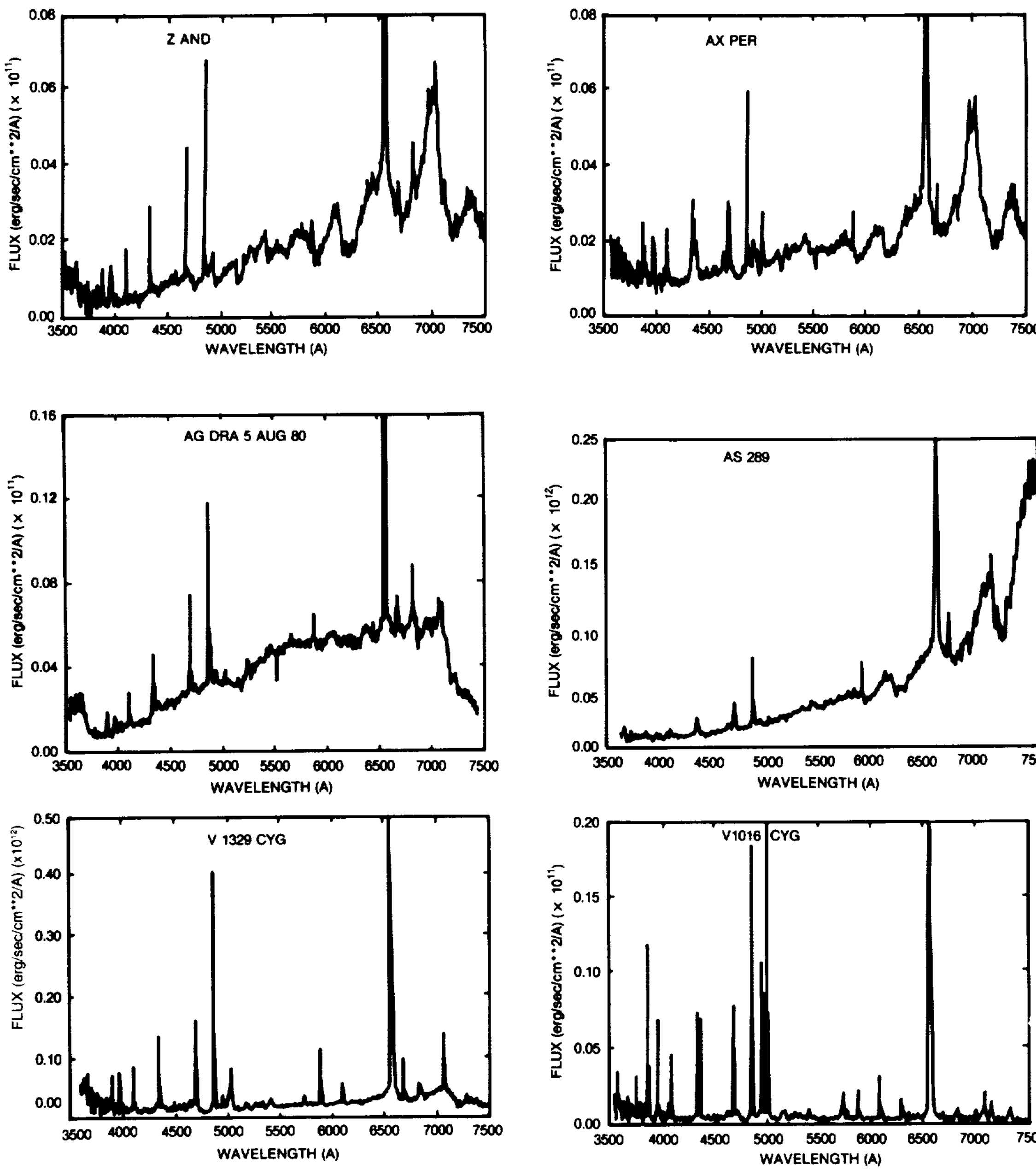


Figure 11.1. The optical spectrum of symbiotic stars Z And, AX Per, AG Dra, AS 289, V1329 Cyg, and V1016 Cyg (Blair et al., 1983).

ized by: (1) a composite stellar spectrum with two apparently conflicting features, and (2) large variability. This is what is generally defined as the *symbiotic phenomenon* (cf. Friedjung and Viotti 1982, p.227). We want to find out the origin of this behavior, and, in particular, to identify and measure the physical mechanism(s) which is (are) responsible for the observed phenomena. We could try a statistical approach to the problem. That is to analyze the observational data of as many symbiotic objects as possible. For instance, we may study the position in the color-color using optical and IR photometry. However, this may easily be misleading, since 100 or 200 objects certainly include objects that have nothing to do with the symbiotic phenomenon, such as unresolved planetary nebulae or extreme VV Cep variables. In addition, these diagrams generally do not tell us anything about the symbiotic mechanism. The sample could also be largely affected by strong selection effects, as many symbiotic objects are close to the Galactic Plane.

Finally, symbiotic stars are variable. That is, the same object may occupy very different places in an observational diagram during different phases of its activity. Thus, a single "event" (i.e., one symbiotic star) is not represented in this diagram by a single point, but by a complex curve. This *representative curve* varies from object to object, and indicates that the physical mechanisms responsible for the symbiotic phenomenon have different weights and shapes in different objects. In other words, *variability is one of the basic observational parameters of a symbiotic object*, and perhaps *the most important one.*[1] In fact, we shall show later that a large progress concerning the symbiotic phenomenon has been made through the analysis of the variability in all the wavelength ranges. For those objects, the majority, which have been observed only a few times or even only once, the information is too poor to be included in a consistent study of the symbiotic phenomenon. This is true even if the observations cover a wide frequency range.

In this chapter, we shall give an overview of the observations of symbiotic stars in different spectral regions. In Chapter 12, we shall discuss the models for symbiotic stars, while Chapter 13 will be devoted to the description of a few well-studied symbiotic objects and discuss their observations in the light of possible models. We finally summarize our present knowledge about the symbiotic phenomenon. This review is not intended to give a full account of all the studies on the symbiotic stars so far made, but only to illustrate the different aspects of the symbiotic phenomenon and to stimulate future researches, Thus, in many cases, we shall quote only a limited number of articles that appeared essential to illustrate the problem. Extensive lists of references can be found in the *Proceedings of the IAU Colloquium 70* (Friedjung and Viotti 1982) and *Colloquium 103* (Mikolajewska et al., 1988), and in Kenyon 1983a; 1983b). Among the several reviews on symbiotic stars, we should quote: Swings (1970), Boyarchuk (1983), Allen (1984a), Kenyon (1986), and Fernandez-Castro (1988).

(1) We must note that frequently symbiotic stars remain at a nearly constant luminosity for a long period of time, even for several years. This is, for instance, the case of Z And during quiescence, and of a number of symbiotic novae (V1016 Cyg, HM Sge, etc.) some years after the outburst. Because of the lack of long enough observations, one symbiotic star could appear stable for a long time only because we have missed the outburst. But this does not disprove that variability is a major feature of the symbiotic phenomenon.

II. GENERAL OVERVIEW OF THE OBSERVATIONS

Observation in different spectral regions essentially gives information about different parts of the atmospheric envelope(s) of a symbiotic object. For instance, as we shall show in the following, the red and near-IR regions are in most cases dominated by what appears to be a cool star's spectrum, while the far-IR is generally associated with thermal dust emission. On the other side, the radio flux provides information about the ionized cloud surrounding the system. The near-UV and the emission lines also are typical features of the diffuse ionized gas near the star(s), while the far-UV and the X-rays are probably associated with a hot star and/or with an accretion disk.

In this chapter, we shall follow the traditional way of first discussing the optical observations, which have provided the distinguishing characteristics of the symbiotic stars. Then the analysis is extended to longer (IR and radio) and shorter wavelengths (UV and X-rays). In addition, a full section will be devoted to polarimetry, since, although this field is so far not well investigated, it should give fundamental information on the structure of the circumstellar environment.

III. THE LIGHT HISTORY OF SYMBIOTIC STARS

III.A. INTRODUCTION

The light history of the symbiotic stars is basic to recognize their different activity phases, to find periodicities which could be related to the presence of a binary (or multiple) system, and, more in general, to separate the different physical subgroups. It should be considered that an obvious reason to use visual photometry, instead of IR or UV, is that it always covers a much longer period of time, and the basic time scales of the symbiotic phenomena are of the order of several hundred days to decades. Perhaps, the ungoing programs of continuous IR and UV monitoring of symbiotic stars will considerably change this viewpoint. In the study of the light curves, a special warning should be made concerning the large contribution to the broad-band photometry of the emission lines whose integrated flux sometimes exceeds that of the continuum. Therefore, the light curves might represent the time-behavior of the nebular region, rather than that of a central stellar object.

Symbiotic stars display in the visible a large variety of light curves, with one or several nova-like outbursts, quasi-periodic oscillations, long periods of relative quiescence at minimum or at maximum luminosity, short-time variability (e.g., flickering), etc. The same object, if observed for a long enough period of time, may present many different kinds of variability. It is therefore impossible to fit all the light curves of symbiotic stars into a common scheme. We might only say that the main character of the variations is that they are *irregular, of moderate amplitude* (one to few magnitudes) with respect to classical novae and cataclysmic variables, and mostly on *long-time scales* (several days to years). But, as illustrated below, small amplitude and short-time scale variations are also present.

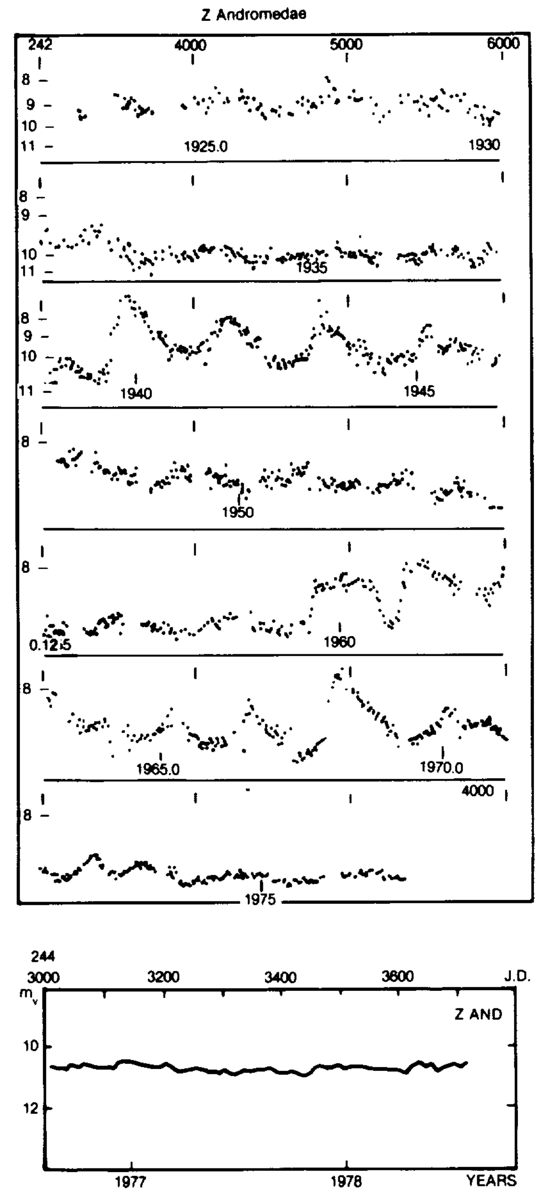


Figure 11.2 The light curve of Z And from 1923 to 1978 (Mattei, 1978) showing a sequence of maxima (or outbursts) separated by 1-2 years, which characterize the active phases of the star, and long-lasting periods of minimum luminosity (quiescence).

III.B. LONG-TERM LIGHT VARIATIONS

The light history of one of the best-studied symbiotic stars, *Z And*, is shown in Figure 11.2.

This light curve, which for a long time has been the ground for many theoretical works on symbiotic stars, is quite irregular. However, two main "trends", or *phases*, can be recognized: as follows (1) a sequence of large amplitude (1-2 magnitudes) oscillations of gradually decreasing amplitude, and (2) quiescent phases with the star near minimum luminosity.

In Z And four and maybe five active phases (1895-1905 and 1914-1923, not in Figure 11.2, 1939-1947 and 1959-1972) have been so far identified in its historical light curve (e.g., Kenyon, 1986). A new minor outburst occurred in March-April 1984 (Mattei, 1987; Viotti et al., 1984), and the star was still active in 1986. At the time of writing this report, it was not yet clear whether this was the beginning of a new active phase, or the 1984 and 1986 maxima were isolated events. The active phases start either abruptly with a rise to maximum (V = 8 or 9) in a few weeks or months, or the main outburst is preceeded by a smaller light maximum. The time interval between two successive light maxima (or minima) is not constant, but varies from 310 to 790 days, with a mean value of 632 days (Mattei, 1978). It should be considered that long-term variations, but with a smaller amplitude, have also been observed during quiescence, especially in the U-band. In this case, these oscillations seem to be periodic, with a mean period of about 757 days (Kenyon and Webbink, 1984) and the maxima are not in phase with the above "outbursts." This behavior will be discussed in more detail in the next section. In the following, we shall describe the period when a symbiotic star is at minimum luminosity (in the visible) as *quiescence* or *quiescent phase*, and the period when the star is highly variable and brighter as *activity* or *active phase*.

Several symbiotic stars show light curves resembling that of Z And with active and quiescent phases. During the last one hundred years, the high-velocity star *AG Dra* underwent several outbursts, reaching a peak magnitude around m_{phot} ~11 (V~10). The maxima are separated by 240 to 710 days (see Robinson, 1969) without evidence of a periodic recurrence of the outbursts. In addition, as in Z And, there are long lasting periods of quiescence from 11 to more than 37 years. During the quiescent phases, the magnitude of AG Dra presents small scale fluctuations (e.g., Belyakina, 1969). The amplitude of these fluctuations increases from visual to near UV, and appears to be periodic with a period of 554 d (Meinunger, 1979).

Another typical case is *CI Cyg*, a symbiotic star showing both outbursts and recurrent minima (see Figure 11-5). Since the beginning of this century, this star displayed five outbursts, the last one in 1975 when it brightened from V = 11 to 8.4 in a few weeks (Belyakina, 1979). Two months later, the luminosity fell to V~11.3 and remained at minimum for about 60 days. CI Cyg brightened again to V~9 at the end of 1975 then gradually faded to V~11 in 1980. The behavior in 1975 is qualitatively similar to that of Z And at the beginning of its active phases. This similarity, however, is only apparent. In fact, the deep 1975 minimum is in phase with several other periodic minima (period of 855 days) recorded in the light curve of CI Cyg, and should be attributed to an eclipse of a binary system, rather than to a phase of minimum activity in between two successive outbursts. If we neglect these periodic eclipses, the overall light curve of CI Cyg during the recent active phases was characterized by a rapid brightening of about two magnitudes in 1979, followed by a four-year decline to the present quiescent phase. This behavior is rather similar to that of the symbiotic novae, which will be discussed later in this section.

In many respects, the classical symbiotic star *BF Cyg* is similar to CI Cyg for showing semiregular minima about one magnitude deep with a period of about 757 d (Pucinskas, 1970), overposed on a much slower trend. As illustrated in Figure 11.3, BF Cyg brightened from m_{pg} = 12-13 to 10 between 1891 and 1894 (Jacchia, 1941). This unrecorded outburst was followed by a very slow fading, interrupted during the active phase around 1916-1922, and continued to present.

Long-term light variations are also observed in the brightest symbiotic star *CH Cyg*. In recent years, this star has varied between V = 6 and 8 (see Figure 22 in Chapter 13). In general, the variations are slow and the fading and brightening phases take several months. However, a much faster luminosity variation took place in September 1984, when the visual light dropped by about 1.5 mag in a few days. This event, associated with a strong radio outburst will be discussed on Section VII.D. Irregular variations on short (~10^2 days, e.g., Kenyon, 1986), and very short (minutes, see Section III.C.) time scales are also present in CH Cyg, and suggest the presence of different mechanisms of variability.

Among symbiotic stars there is a small group of objects showing a light curve quite different from those previously described, which actually characterize the large majority of the stars com-

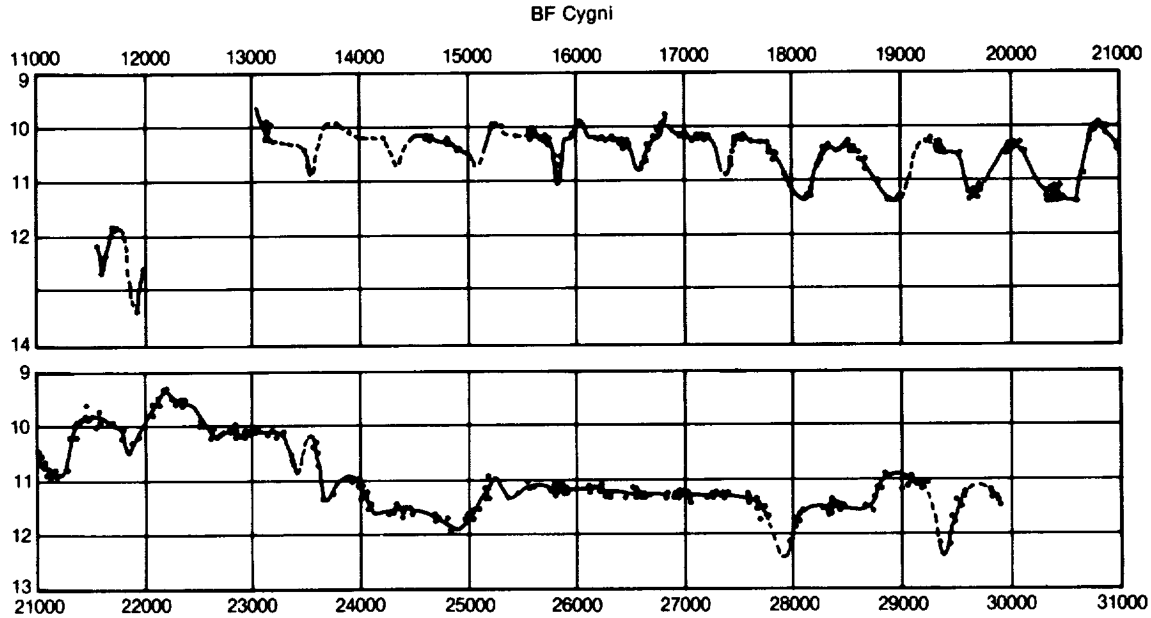


Figure 11-3 The light curve of BF Cyg (Jacchia, 1941). There is a secular decrease of luminosity since the end of the last century interrupted by the active phase around 1916-22, and a sequence of quasi-regular minima atttributed to eclipses in a binary system with a period of 757 d.

monly called symbiotic. They are the *symbiotic novae*. In 1964, a nova-like event was recorded in Cygnus (FitzGerald et al., 1966) in a faint (B~ 15^m) M star, *MHα 328-116*, known to have strong Hα in emission (Merrill and Burwell, 1950). The luminosity of this object, better known as *V1016 Cyg*, gradually increased in the following years until B = 11 mag at the beginning of 1968 (see Figure 11-4). Since that time, the luminosity of V1016 Cyg has remained nearly constant. This behavior (and the associated spectral variations, which will be discussed in the next section) is reminiscent of that of novae, but with a smaller

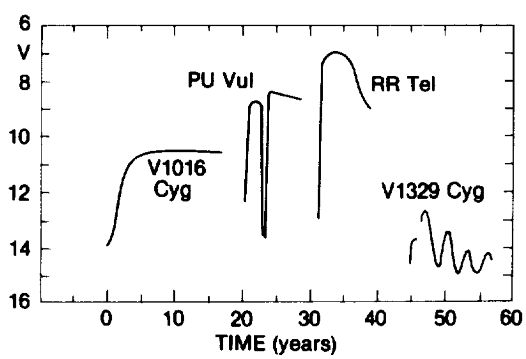


Figure 11-4 . Schematic light curves of the symbiotic novae. V1016 Cyg, PU Vul, RR Tel, and V1329 Cyg (=HBV 475).

amplitude and an exceptionally long time scale. In addition, in V1016 Cyg, no decline in the optical luminosity of this star was observed until now. A similar behavior was more recently displayed by *HM Sge*. This star brightened from V>17 to 11 mag in a few months, and still is at maximum at the time of writing this report. Both stars, V1016 Cyg and HM Sge, have been included among symbiotic stars because of their very rich emission line spectrum, and their red-near IR excess showing marginal presence of molecular (TiO) absorption bands, confirming their symbiotic nature.

There are a few more symbiotic stars that had a historical light curve with one single major outburst. Allen (1980) listed seven stars having the character of very slow novae, or of *symbiotic novae*: AG Peg, RT Ser, RR Tel, V1016 Cyg, V1329 Cyg, HM Sge, and AS 239 (V2110 Oph). To this list, we have to add the nova-like variable PU Vul, which "exploded" in 1978. In these objects, the rise to maximum is much slower than in the classical novae (but in two cases, RR Tel and HM Sge the brightening phase was not recorded). The following phase of luminosity decrease is even slower and took from one decade to more than one century. In fact, no decline has so far been observed in V1016 Cyg, HM Sge, and PU Vul. The fading in RR Tel and probably AG Peg was gradual, while in V1329 Cyg, it was characterized by large light oscillations. In PU Vul, a deep minimum was observed just one year after its outburst. In these two objects, the minima could be caused by eclipses in a binary system, but the PU Vul deep minimum could be due to temporary occultation by dust (Friedjung et al., 1984). In any case, as illustrated by Figure 11-4, we can hardly speak of a typical light curve of symbiotic novae, except for the fairly steep and large brightening with respect to the other symbiotic stars. These objects will be discussed in Chapter 13, Section IV.

III.C. SHORT TIME VARIATIONS

The light curve of symbiotic stars is characterized by irregular variations of short (days and minutes) time scales overimposed on the long-term trend described above. In general, this variability is poorly known and in many cases its reality is questionable. In fact, our knowledge on the light behavior of symbiotic stars, in most cases, is based on visual estimates that are intrinsically uncertain by a few tenths of magnitudes. Actually, only a few objects are included in current monitoring programs using standard procedures of observation and reduction. In most cases, our knowledge is based on visual estimates that are uncertain by a few tenths of a magnitude. For instance, the light curve of Z And shows several small amplitude fluctuations besides the already discussed long-term behavior, which are probable real. Night-to-night UBV variations in CI Cyg have been claimed by Burchi et al. (1984) and Chochol et al. (1984). The amplitude seems to be larger at shorter wavelengths.

Intermediate filter photometry is more appropriate for the study of the nature of the rapid variations (Kenyon 1986). Short-term fluctuations on a time scale of minutes have been observed in CH Cyg by Cester (1968) and Wallerstein (1968). As in the case of CI Cyg, the amplitude increases with decreasing wavelength. The phenomenon is similar to the "flickering" observed in dwarf novae, and could be a means to investigate the nature of the hot component in symbiotic systems. However, a survey of Walker (1977) suggests that the majority of symbiotic stars are constant to 1 *per cent* over time scales of 20 minutes to 2 hours. We finally note that a large flickering is present in the recurrent novae T CrB and RS Oph, stars that are frequently included among symbiotic stars.

III.D. PERIODIC LIGHT VARIATIONS

As discussed above, in some light curves, one can identify a series of minima occurring at regular, or quasi-regular time intervals. About one dozen periodic minima were discovered by Hoffleit (1968) in the Maria Mitchell Observatory plots of CI Cyg covering the period 1916-1967 (Figure 11-5). The periodicity of 855 d was confirmed by new extensive photometric studies carried out among others by Belyakina (1974). As in other symbiotic stars, during these minima CI Cyg becomes redder, suggesting that the light decrease is associated with fadings or eclipses of the blue spectral component. Periodic minima were also discovered in the southern sky symbiotic AR Pav by Mayall (1937), who derived a period of 605 d. Semiregular variations are also present in BF Cyg as discussed above (see Figure 11-3), while in other cases, such as Z And during its active phases, the light minima do not suggest a periodic trend.

It would be of crucial importance, for understanding the symbiotic stars, to find out any periodic phenomenon in the observations that could be associated with orbital motion in a binary system, or with stellar rotation or pulsation. The problem is to separate any "regular trend" from the irregular variations associated with the large scale activity, and with the microvariability illustrated in the previous sections. For instance, the minima of CI Cyg are clearly present in the whole recorded light curve, independently on the "activity." This is best illustrated in Figure 11-5 that show the recent light curve of CI Cyg.

During quiescence the recurrent minima are difficult to identify, since the star's minimum luminosity ($V \sim 11.1$) is only a few tenths of a magnitude fainter that the mean luminosity at

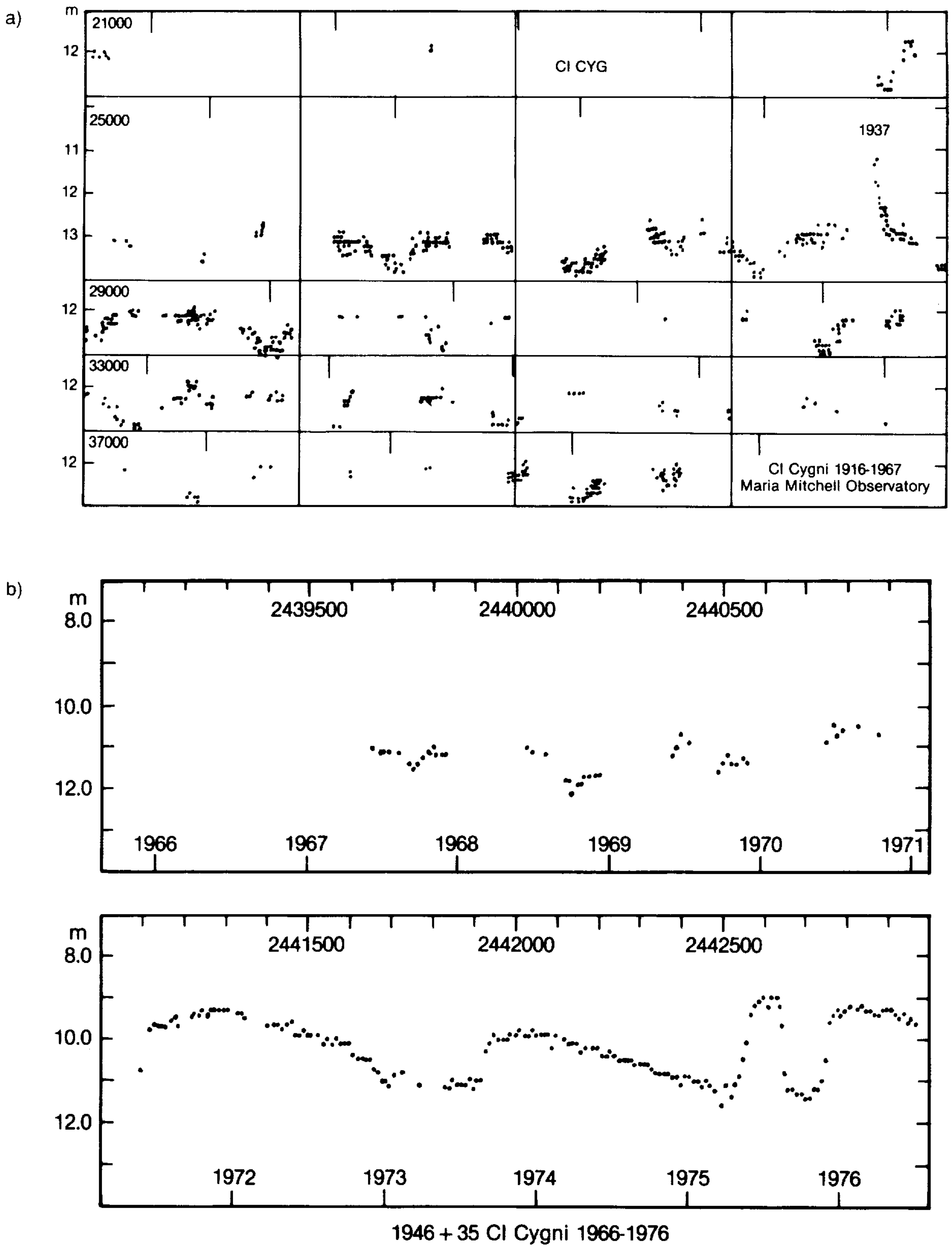


Figure 11-5. The light curve of CI Cyg: (a) from 1916 to 1967 (Hoffleit, 1968), and (b) from 1967 to 1976 (Mattei, 1976).

quiescence (V ~ 10.8-11.0), and this difference is of the same order of magnitude as the observational errors and as the irregular light fluctuations. On the contrary, when CI Cyg is in outburst, the minima are very deep. It is worth noting that during these phases, the star attains the same minimum magnitude as during the minima in quiescence. Thus, the minimum luminosity is independent on the phase of activity, and might suggest complete eclipse of the variable hot component, as also confirmed by Belyakina (1979) results that the minima are deeper in the U-band.

During quiescence, the light curves of many symbiotic stars present quasi regular long term fluctuations. Figure 11-6 shows the light curve of AG Peg during 1964-1984 characterized by several recurrent minima separated by about 827 d (Belyakina, 1985). The amplitude is larger in B and U. A similar behavior was found in other symbiotics such as AG Dra (Meinunger, 1979), AX Per (Kenyon, 1982), SY Mus (Kenyon and Bateson, 1984). Also, these variations can be attributed to partial eclipses of a binary system. Small-scale periodic oscillations of the visual luminosity of RR Tel are, on the contrary, attributed to the pulsation of its Mira component (Heck and Manfroid, 1985; Kenyon and Bateson, 1984).

BX Mon represents an extreme case of quasi-periodic variability. From a study of a collection of Harvard plates taken between 1890 and 1940, Mayall (1940) concluded that BX Mon was a very long period variable with P = 1380 d, m_{pg} (max) = 10.02 and m_{pg} (min) = 13.05. Thus, this star should be an extreme Mira-type variable with prominent symbiotic characteristics. However, the periodicity has not been confirmed (Iijima, 1985), and the large amplitude photometric variations could be attributed to the hot component activity, rather than to a Mira variable (Viotti et al., 1986).

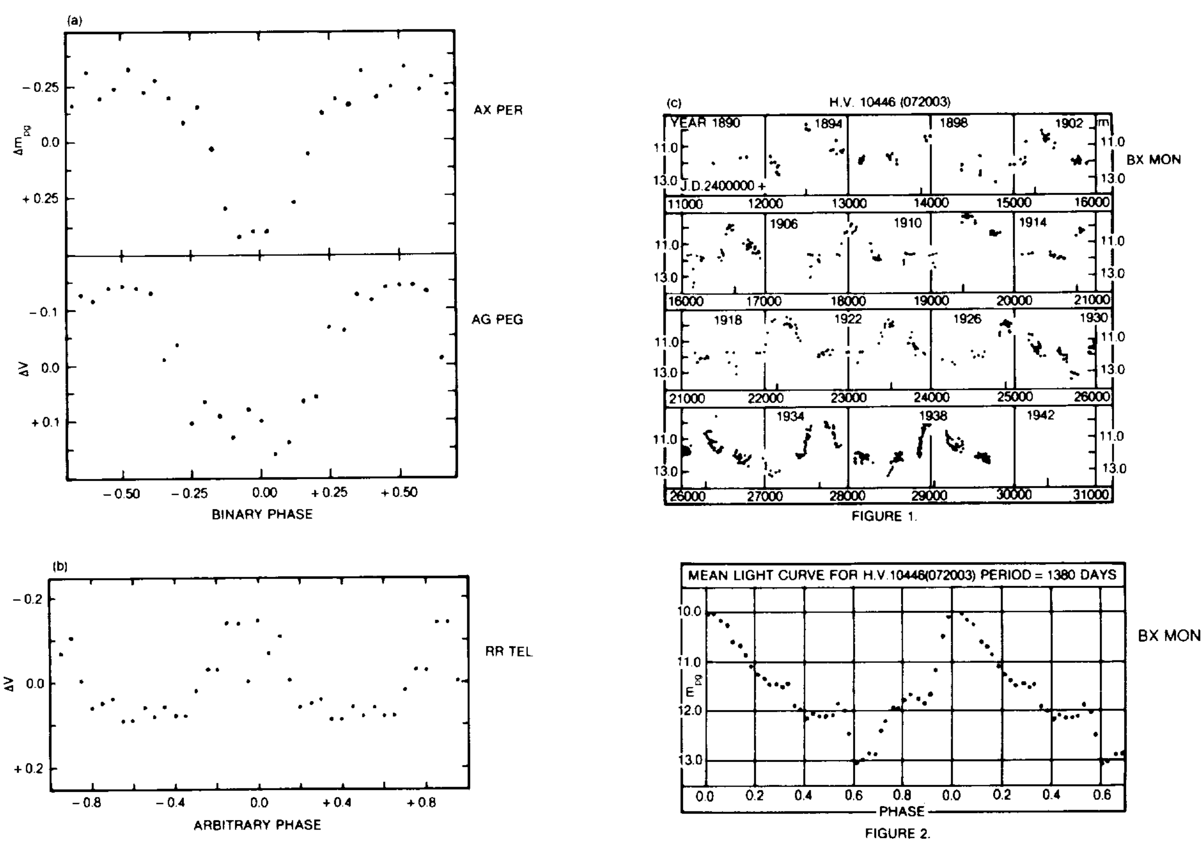


Figure 11-6. Periodic light variations of symbiotic stars: AX Per, AG Peg, RR Tel (Kenyon, 1986), and BX Mon (Mayall, 1940).

It is clear from the above considerations that the presence of periodic light variations does not represent an evidence of binarity. Only observations in different ranges can provide an answer to this problem. Table 11-1 summarizes the main parameters of the regular, or quasi-regular light variation observed in symbiotic stars.

clearly distinguish among the two, irregular and periodic, types of long-term variation, since they are associated with two different phenomena. Most symbiotic stars show small amplitude (one-tenth of magnitude) fluctuations on time scales from days to minutes. In many cases, the photometric accuracy is not large enough to confirm these variations and their behavior, but the amplitude seems to generally increase towards shorter wavelengths. Much work is still to be done in this field.

TABLE 11-1. BASIC DATA ON THE OPTICAL LIGHT VARIATIONS IN SYMBIOTIC STARS.

Star		Maximum (JD) 2400000+	Period days	Ref.
Z	And		756.85	1
EG	And	43200.5	470	2
CI	Cyg	11902	855.25	3,4
AG	Dra		554	5
RW	Hya	21519.2±4.2	372.45±0.3	1
BX	Mon		1380	6
SY	Mus	35175.7±15.7	627.0 ±1.2	7
AR	Pav		605	8
AG	Peg	42710.1 ±6.0	816.5 ±0.9	9
RR	Tel	42550.7±18.7	374.2 ±3.8	10

Notes to the table. (1) Kenyon and Webbink (1984). (2) Smith (1980). (3) Greenstein (1937). (4) Belyakina (1974). (5) Meinunger (1979). (6) Mayall (1940). (9) Fernie (1985). (10) Kenyon and Bateson (1984).

As a conclusion of this section on the light history of symbiotic stars, there is a large variety of shape, amplitude, and time scale in the light curves of different objects. But also, the same object generally displays different types of variability at different epochs, and variations on long and very long time scales to short and very short ones. The "secular" behaviour is known only in a relatively small number of objects (a few dozen), obviously because it requires observations for several decades. But also observations for more than one century for a few objects have not helped the understanding of their long-term behavior. The variations are, in general, irregular. The regular or quasi-regular fluctuations found in several objects are attributed to recurrent eclipses of a binary system. In many cases, this has been confirmed by the spectroscopic observations. It is important in any study of symbiotic stars to

IV. THE VISIBLE SPECTRUM

In this section we shall describe the main features of the visible spectrum of symbiotic stars, pointing out both the spectral anomalies and the features that are commonly seen in "normal" stellar spectra. In general, three main spectral components are identified in the optical spectrum of symbiotic stars: (1) the cool stellar spectrum, (2) the blue continuum excess, (3) and the rich emission line spectrum. These components can be easily seen in the spectra reproduced in Figure 11-7. In the following we shall separately describe the three spectral features.

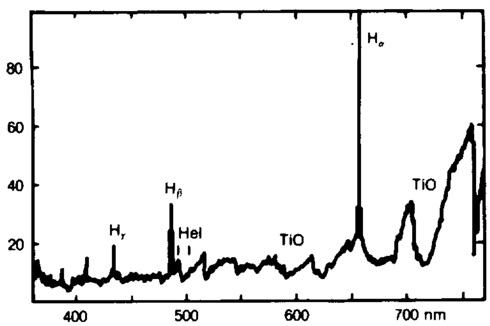


Figure 11-7 The optical spectrum of BX Mon from 3800 to 7600 A (Viotti et al. 1986). The TiO absorption bands are clearly visible in the red part of the spectrum. Shortwards of about 6000 A, the late type spectrum is masked by the blue continuum. Note the prominent emission lines of hydrogen and helium.

IV.A. THE RED COMPONENT

Most of the symbiotic stars have a red continuum that rises towards longer wavelengths. Metallic absorption lines (e.g., of FeI) or bands of molecular species (e.g., TiO, VO, C2) that are attributed to photospheric absorptions on a cool-star continuum have been identified in these continua. In Figure 11.7, the prominent TiO bands typical of an intermediate M-type giant are clearly seen in BX Mon.

The cool-star spectral features are easily seen in the red, near-IR where the cool spectrum normally dominates. As discussed later, these objects have visual/IR color indices typical of a late-type star and are therefore called S-type symbiotics (where S stands for "stellar"). In many cases also, absorptions from the resonance lines of CaI and CaII have been identified in the blue, but normally these lines are masked by the strong blue continuum excess.

A major problem is represented by the blue continuum, which is variable and extends to longer wavelengths. Thus the cool-star absorption lines are *veiled*, i.e., their central depth is reduced by an amount, that depends on the wavelength and that is variable in time. This is illustrated in Figure 11-8, which shows the high-resolution spectrum of CH Cyg during different epochs.

CI Cyg is another example of variable veiling of the blue spectral component which could mimic an apparent time variability of the cool spectral component. From the analysis of the 1975 spectrum of this star, Audouze et al. (1981) claimed the occurrence of an s-process episode with the considerable enhancement of the elements produced from the s-process. However, their observations refer to a phase of minimum luminosity when the blue region was dominated by the cool spectral component. Therefore, the observed large spectral change was only due to the disappearance of the blue, shell-type spectrum formed during the outburst, dominated by singly ionized metal lines, and the emerging of the M-spectrum with several FeI lines, wrongly identified by Audouze et al. as lines of rare earths (Kenyon et al. 1982).

Several authors have provided the spectral classification of symbiotic stars, but frequently there is a large spread in the individual classifications for the same star. For instance, AG Dra has been variously classified as K1II, G5, K3III, or K0I (Kenyon, 1986), and one could argue that the cool component of AG Dra is highly variable, but this has not been confirmed by recent accurate studies. More probably, the spectral classification of this star is largely affected by the variable blue spectral component, as discussed above for the cases of CH Cyg and CI Cyg. Actually, the classical (old) criteria of spectral classification are based on the relative strength of absorption lines and bands in the blue region, while only recently the yellow-red region has been more extensively used for the cool stars. Most of the reported classification of symbiotic stars were based on blue spectra, where the absorption features are seriously masked by the variable blue continuum and by the emission lines. Thus, one should take care of these classifications, especially the oldest ones.

Spectral classification of the cool components of the symbiotic stars mostly based on near-IR spectrophotometry, has been performed by, among others, Kenyon and Fernandez-Castro (1987), and Schulte-Ladbeck (1988). Typically, the symbiotic stars show deep TiO absorption bands whose strength suggests a spectral type from early M (e.g., AG Peg) to intermediate M (Z

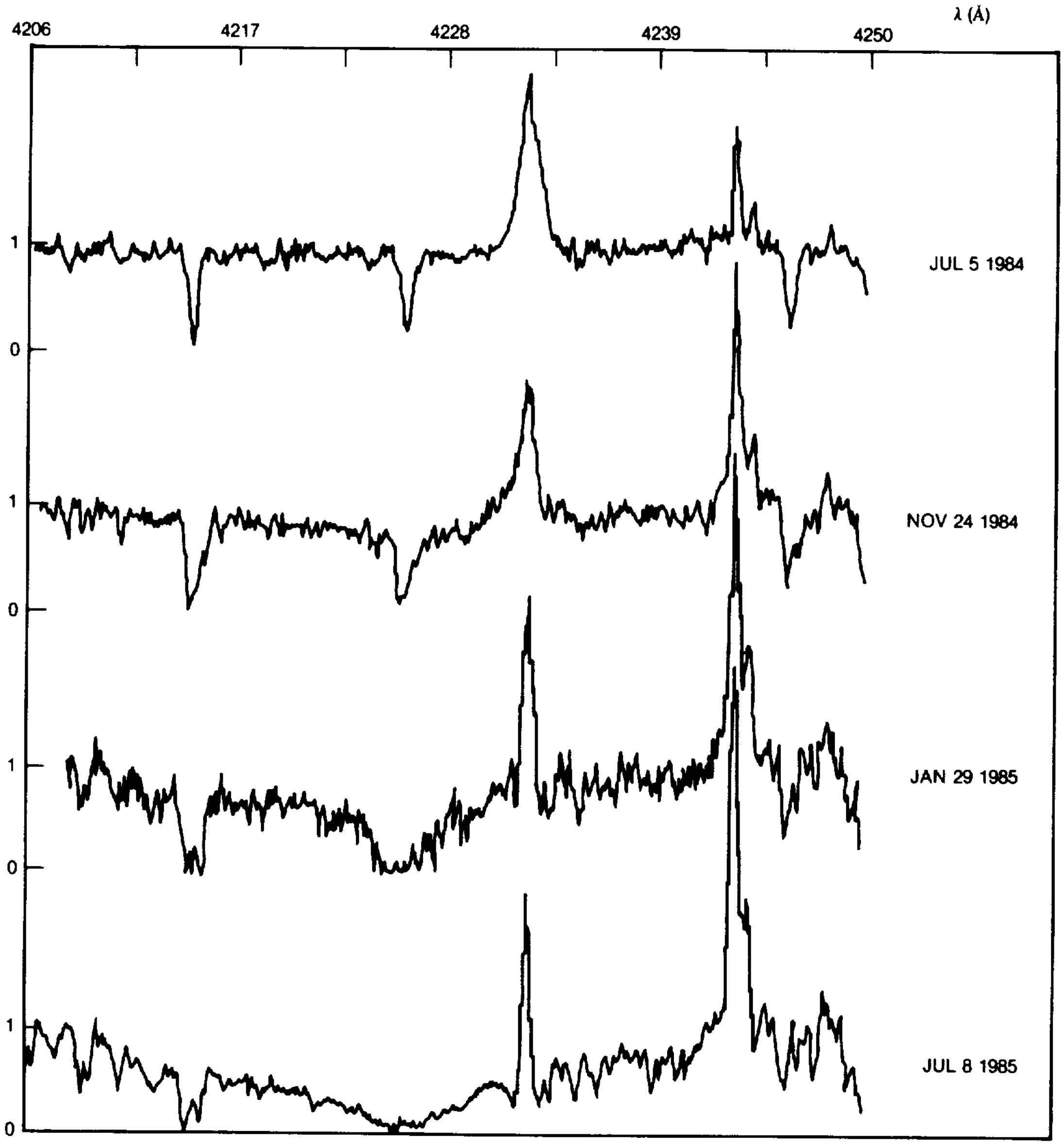
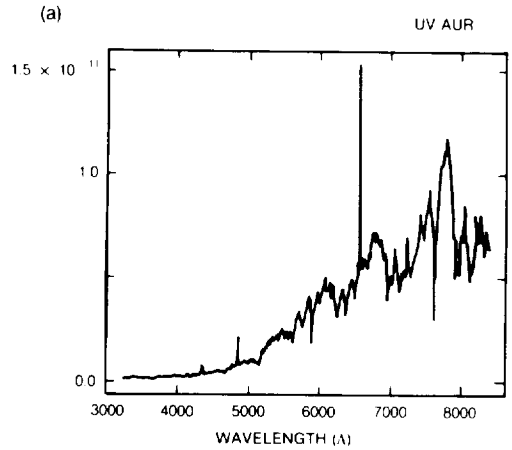


Figure 11-8. The high resolution spectrum of CH Cyg during two different luminosity phases: (a) 5 July 1984) (V~6.0); (b) 8 July 1985 (V~7.8). The broad CaI absorption, associated with the spectrum of the M component is strong at minimum, but invisible at maximum. Note the strong "shell" absorptions of FeI present all the time and the prominent FeII emission at 4233 A (courtesy of M. Hack).

And, CI Cyg) and late M-type (e.g., V1329 Cyg). A few objects included in the symbiotic category have a hotter cool components of type F or G. Examples are M1-2 (type G2), HD 330036 (F5III-IV, Lutz, 1984), and HD 149427 (F-type, Webster, 1966). These stars have been called "yellow symbiotics" by Glass and Webster (1973). They are also known, from their IR spectrum, as D'-type symbiotics (Allen, 1982). Another case is the symbiotic star AG Dra which, as seen above, is characterized by a K-giant spectral component. This star is interesting also for its large radial velocity (-140 kms^{-1}, Roman, 1953), and high galactic latitude (+41°). Thus AG Dra is a typical Pop II object, and probably not the only one, among symbiotic stars, as we shall discuss in the summary section of this chapter.

C-8.



In a few symbiotic objects, molecular carbon bands, instead of TiO ones, have been identified. This is, for instance, the case of the bright galactic object UV Aur (Figure 11-9). Other examples are UKS Ce-1 and Weaver's star in our Galaxy (Schulte-Ladbeck et al., 1988), and S63 in the Large Magellanic Cloud (Figure 11-9). The latter is one of the two symbiotic objects so far identified in the LMC (Allen, 1982) and could suggest a higher frequency of carbon symbiotics in LMC than in our Galaxy. Actually, it is well known that in the LMC, the frequency of carbon stars among late-type stars is much larger

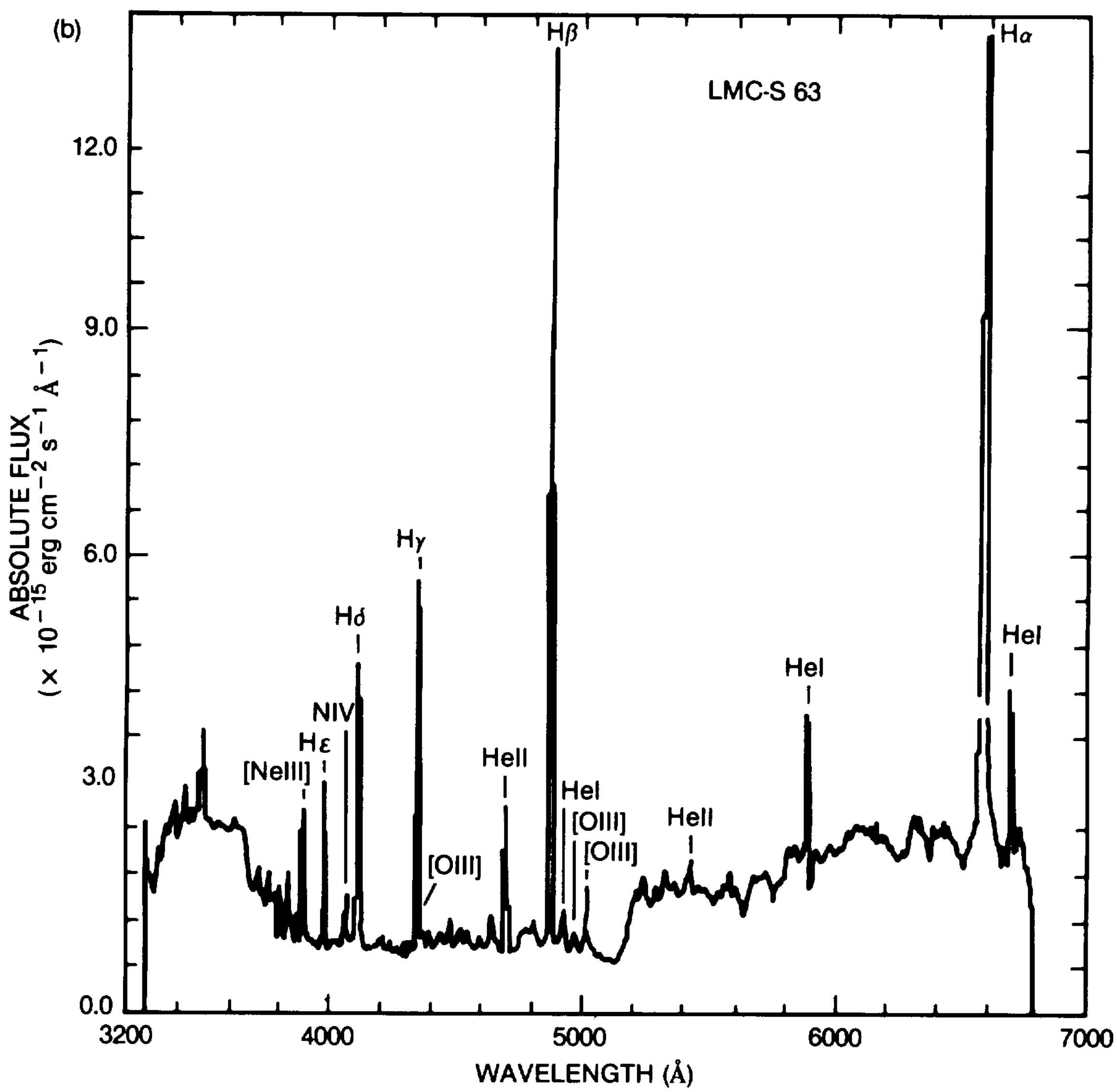


Figure 11-9. The optical spectrum of two carbon symbiotic stars, UV Aur (Kenyon, 1986), and S63 in the Large Magellanic Cloud (Kafatos et al., 1983).

than in our Galaxy. It would be important to investigate in the future if the frequency of carbon spectra in the LMC symbiotics is higher by a similar amount. This could provide crucial information about the origin of symbiotic stars.

In some symbiotic stars, the red continuum is an extension of the IR excess, which is attributed to thermal dust emission (the so-called D-type symbiotic stars, see Section VI). This is, for instance, the case of V1016 Cyg (Figure 11-1), where the contribution to the red of a cool photospheric spectrum should be small and the photospheric absorption features hard to identify. Actually, in this star, the molecular absorption bands seem to be present but very weak (Mammano and Ciatti, 1975). Also, in other D-type symbiotic stars such as RR Tel and HM Sge, the M-type features are hard to be seen (e.g., Thackeray, 1977). We shall come back to the problem of the spectral classification of the cool stellar spectrun in Section VI devoted to the IR observations.

IV.B. THE BLUE SPECTRUM

As discussed above, the main spectral feature that distinguishes the symbiotic stars from normal cool giants, is the presence in their visible spectrum of strong emission lines and of a "blue" continuum. In normal late-type stars, emission lines are present at the shortest wavelengths of the visible spectrum, and in the space ultraviolet, where the photospheric continuum rapidly drops. In the Sun, the photospheric spectrum extends to about 2000 A, where it turns to a rich emission line spectrum. In symbiotic stars, emission lines—of both low and high ionization species, and not only the Balmer series—are already seen in the visible spectrum, and around 4,000-5,000 A, there is a gradual transition from the cool photospheric spectrum, which dominates the longer wavelength region, to a "blue" continuum. This continuum extends to shorter wavelengths and to the space ultraviolet, and frequently presents a Balmer continuum excess. Typical cases of symbiotic stars with a positive Balmer discontinuity are Z And, BF Cyg, V1016 Cyg (Figure 11-1), AG Dra, V443 Her, SY Mus, AG Peg, ect. (see O'Dell 1967; Blair et al., 1983; Allen, 1984b; and Kenyon, 1986). The blue continuum of the symbiotic nova V1329 Cyg (Figure 11-10) is peculiar not only for the large Balmer discontinuity, but also for the presence of several very broad humps. Crampton et al. (1970) attributed them to emission lines typical of a Wolf Rayet star of type WN5. These features have also been observed by Baratta et al. (1974) in their objective prism spectra. In general, the violet end of the visible spectrum is not well recorded in the great majority of the observations, while this should give precious information about the structure of the emitting region or about the hot star atmosphere.

The blue continuum is highly variable (with respect to the cool spectrum), and its variability is mainly responsible for the behavior of the visual light curve of the symbiotic stars. Generally, symbiotic stars near maximum become bluer, while their colors are redder at minimum. But their trend is not well established, and red maxima have also been observed. During the maxima, the cool spectrum may be completely veiled by the enhanced blue continuum, and the photospheric absorptions disappear, while the color indices become bluer. If an eclipse occurs, the blue continuum disappears, and the red spectrum emerges, making the color index redder, as, for instance, observed in CI Cyg.

IV.C. THE OPTICAL EMISSION LINE SPECTRUM

Emission lines, both permitted and forbidden, belonging to a wide range of ionization energy and line strength have been identified in the optical spectrum of symbiotic stars. From neutral species up to six times ionized iron and calcium have been observed in the spectrum of the same object. Table 11-2 gives the atomic species identified in the emission spectrum of two well-studied symbiotic stars, Z And and RR Tel.

These species are commonly identified in the spectrum of symbiotic stars during quiescence and in symbiotic novae some time (months or years) after the beginning of the outburst. Most emission lines are those observed in the spectra of diffuse and planetary nebulae, and for this reason some authors suggested a physical link between symbiotic stars and planetary nebulae. Indeed,

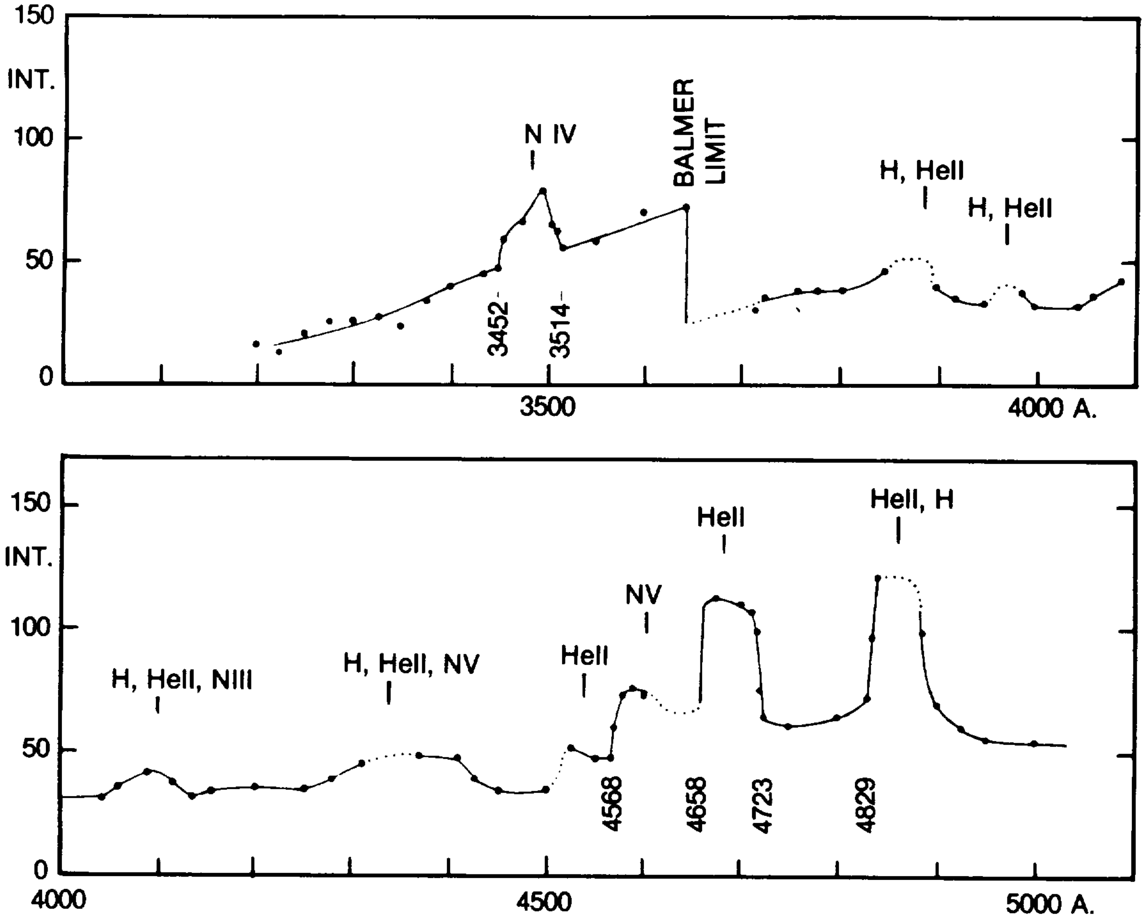


Figure 11-10. The blue continuum of V1329 Cyg in November 1969 (Crampton et al., 1970). Several WR features and the Balmer discontinuity are clearly visible.

TABLE 11-2. ATOMIC SPECIES IDENTIFIED IN EMISSION AND ABSORPTION IN THE OPTICAL SPECTRUM OF THE SYMBIOTIC STARS Z AND AND RR TEL.

Star	Emission Lines	Ref.	Abs. Lines	Ref.
Z And	H, HeI,II, CII,III,IV NIII, OII,III, NeIII,V, MgII, CaII, TiII, FeII,III?,VII, 6380 A	1,2,3	TiO, VO:	1,2
RR Tel	H, HeI,II, CII,III,IV NII,III,V, OI,II,III,IV NeIII,IV,V, MgI,II, SiII, SII,III, Cl IV:, AIII,IV,V, KIV,V, CaII,IV:,V, MnIV,V?, MnVI?, FeII,III,IV,V,VI,VII, 6830 A	4	TiO	4

References: (1) Swings and Struve (1941); (2) Boyarchuk (1968a,b); (3) Altamore et al. (1974); (4) Thackeray (1977).

the observation of intense forbidden lines indicates the presence of a diluted, highly ionized medium near or around the symbiotic object. Strong high-ionization lines (HeII, NIII, [OIII], [NeIII], [NeV], [FeVII]) have, in fact, been identified in the spectra of many symbiotics, and have long since raised the problem of their origin, e.g., whether collisionally or radiatively ionized (for instance, Ilowaisky and Wallerstein, 1968). Of particular interest is the intriguing problem of the still unidentified broad features at 6830 and 7088 A. These emission lines are present in the optical spectrum of symbiotic stars with the highest ionization level, such as RR Tel, He 2-38, and H 2-38, and probably are associated with a so far unknown highly ionized species (Allen, 1980a). It should be noted that in RR Tel and in other symbiotic novae, these features appeared in the latest stages of their spectral evolution, when the optical spectrum displayed the highest ionization level. Also, in some cases coronal lines have been observed: [FeX] has been reported in CI Cyg (Swings and Struve, 1940), and possibly in RX Pup (Swings and Klutz, 1976), while [FeXIII] has been identified in R Aqr by Zirin (1976). We should recall that still higher ionization levels have been observed in the recurrent novae T CrB ([FeX], [FeXIV]), and RS Oph ([FeX], [FeXI], [FeXIV], [AX], and [NiXII]; see Kenyon, 1986). These latter objects have, in fact, been often included in the category of symbiotic stars.

A major problem of the symbiotic phenomenon is the simultaneous presence of both high (e.g., [FeVII])-and low (e.g., FeII, [FeII])-ionization emission lines, implying the existence of a very wide temperature range in the environment of symbiotic stars. In this regard, their spectrum resembles fairly well that of the solar chromosphere, transition region and corona, and this could again suggest that a similar physical process is acting in the environment of the Sun and of, at least, some symbiotic stars.

Emission lines are variable, in both intensity and shape. As a rule, the line excitation is higher when the star is at minimum luminosity, and *vice versa*. RX Pup, during its bright stage of 1960-75 (V=8.5), showed in the optical hydrogen and ionized iron emission lines, while at minimum (in 1905, 1940, and 1981 to present, V~13), the star displayed a large ionization range up to [NeV] and [FeVII] (Allen and Wright, 1988). During outburst, the mean line excitation generally decreases, and P Cygni profiles are seen with absorption components displaced to shorter wavelengths by a few hundreds of km s^{-1}. Swings and Struve (1941) measured in Z And velocities from -83 to -186 km s^{-1}. At maximum, the spectrum of CI Cyg and RR Tel resembled that of an F supergiant with a few emission lines (hydrogen and helium) and absorption lines of singly ionized metals (Thackeray, 1950; Belyakina, 1979). Larger P Cygni velocities have occasionally been observed in a number of objects, such as BI Cru (Henize and Carlson, 1980), AG Peg (Merrill, 1951), RX Pup (Klutz, 1979), and RR Tel (Pottasch and Varsawsky, 1960). Radial velocities of the absorption components range from few to several hundreds km s^{-1}. After the outburst, during the fading phase and at minimum, the degree of ionization increases with the gradual appearance of higher and higher ionization lines (e.g., Thackeray, 1977). Thus, the behavior is rather similar to that of novae, except for the much shorter time scales. Spectral variability in individual objects will be discussed in more detail in Chapter 13.

In additon to the spectroscopic changes associated with the long-term light variability, many authors have noticed spectral variations on short time scales. For instance, night-to-night fluctuations of emission-line intensities have been observed in Z And (Kenyon, 1986). Scanner observations of CH Cyg by Walker et al. (1969) revealed that the Balmer excess is rapidly varying on time scales of minutes. Several other examples can be found in the literature (most of which are reported in Kenyon's thesis and book (Kenyon 1983b, 1986)), but in the majority of cases, the observations are too scattered, and the authors do not provide a quantitative picture of the phenomenon. So, it is not possible at this stage to have a clear idea about amplitudes, time scales, and trends of these fluctuations. This is one field that should require more observational (and systematic) work in the future.

IV.D. LINE PROFILES

The high-resolution spectroscopy of most symbiotic stars has revealed the existence of emission lines with a very complex profile. This is best illustrated by the Hα line, which presents a large variety of shapes in different objects, and, for the same object, in different epochs. Figure 11-11 shows the Hα profiles in a number of symbiotic stars.

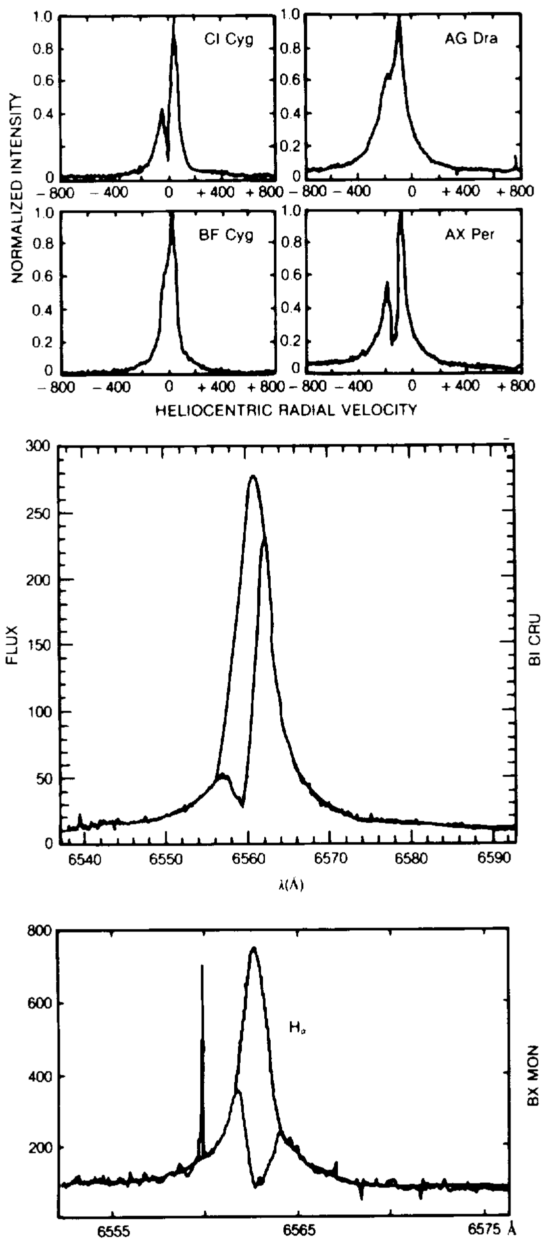


Figure 11-11. Hα profiles in symbiotic stars (Kenyon, 1986; Viotti et al., 1986 Rossi et al., 1988).

Hα profiles in individual objects were studied among others by Smith and Bopp (1981: AG Dra), Oliversen et al. (1985: EG And), Viotti et al. (1986: BX Mon), Rossi et al. (1988: BI Cru), etc. Generally Hα is characterized by a central peak broadened by one to a few 100 km s^{-1} (FWHM). A P Cygni profile is frequently observed again with an absorption component violet-shifted by $-100 \div -300$ km s^{-1}, although sometimes red-shifted absorptions have also been found. In many of those objects where the P Cygni absorption is not seen, the Hα peak appears asymmetric, sometimes with a bump in the emission wing. Hα is generally variable in intensity and shape on a long time scale, probably as the result of the stellar "activity" and/or orbital motion. Oliversen and Anderson (1982b) described the change for the Hα profile in AG Dra as a function of the phase of the U-band photometric curve. Iijima (1985) noted that in BX Mon, Hα changed from direct to inverse P Cygni profile. Oliversen et al. (1985) studied the Hα profile variation in EG And during one cycle of the suggested 470-day period. They found dramatic variations of the line equivalent width and profile, with the line changing from strong emission peak to broad central absorption with weak side emissions (Figure 11-12).

Extended broad wings are another frequently observed feature of Hα; they are generally better seen in the middle resolution spectrograms. Broad wings are also seen in other strong emission lines, but a systematic study of these features has not yet been made, mostly because of the lack of high S/N optical spectra. As discussed later in this chapter, these features are also present in the ultraviolet spectra of several symbiotics. P Cygni profiles have been observed in several optical lines (H, HeI, FeII, etc.) during different phases of the history of symbiotic stars. For this reason, many authors classified some symbiotics as Be or P Cygni stars (e.g., Beals, 1951). The displacement of the P Cygni absorptions is from one to several hundreds of km s^{-1}, again depending on the symbiotic phase. In 1950, the HeI 3888 line in AG Peg developed multiple absorption components at velocities from -72 to -382 km s^{-1}, a behavior similar to that of novae (Kenyon, 1986).

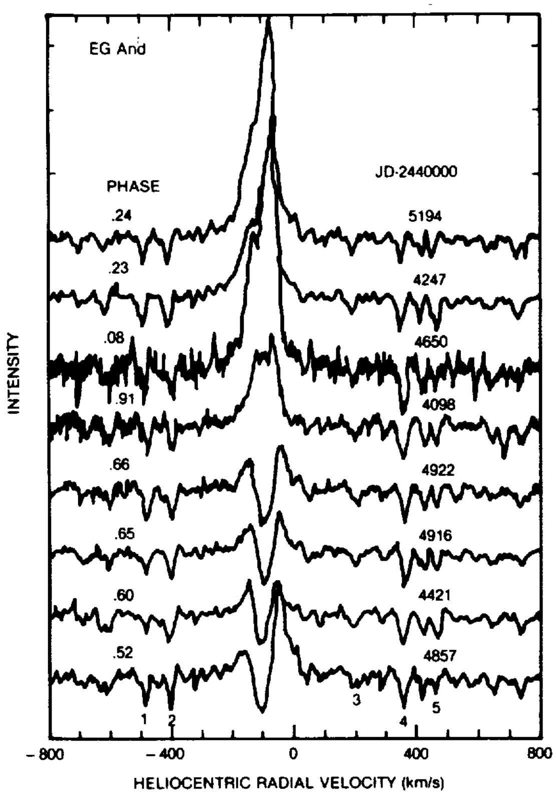


Figure 11-12. Variation of the Hα profile in EG And during August 1979 to August 1982 as a function of the phase of the Smith (1980) curve (Oliversen et al., 1985). Photospheric absorption features of neutral elements are seen on the stellar red continuum.

As regards the "narrow" emission components, at high resolution their width is of the order of a few to several 10 km s^{-1}. When measured with great accuracy, the width appears different in different ionic species. For instance, Muratorio and Friedjung (1982) found that in V1016 Cyg, the FWHM of the emission lines varies from 40-60 km s^{-1} for the singly ionized metal lines to 110-150 km s^{-1} for the highly ionized lines of [NeIII], [AIV], [NeIV], and [FeVII].

V1329 Cyg, RX Pup, HM Sge, RR Tel, and other symbiotics display, or have displayed during some phases of their history WR features (Crampton et al., 1970; Thackeray and Webster, 1974; Brown et al. 1978), but not the OVI characteristic of very high excitation (see Allen, 1980). As discussed above, V1329 Cyg presents very broad WR features, which are better seen at low resolution. Similar features could be present in other symbiotic objects but are difficult to observe. This raises again the need of high-quality observational data.

At high resolution, the strongest emission lines frequently exhibit a multiple structure sometimes similar to that observed in the decline phase of novae. A typical example is again V1329 Cyg. According to Crampton et al. (1970), after the outburst, this star displayed [NeIII] and [OIII] lines with a dozen or more narrow emission components from -240 km s^{-1} to +250 km s^{-1}. This multiple structure is still present to date (Figure 11-13) and indicates that the feature was not episodic and only related to the outburst.

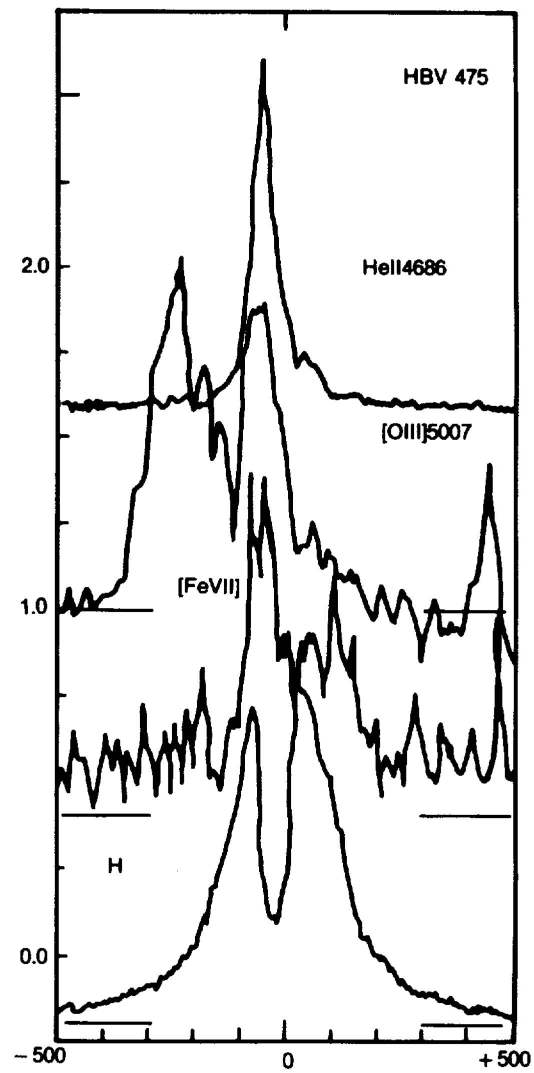


Figure 11-13. Emission line profiles in V1329 Cyg (Tamura 1988). Note the very different shape of lines of different species.

IV.E. RADIAL VELOCITY

The knowledge of the radial velocity of a symbiotic system is basic for the determination to which populations it belongs, but also to find any periodicity related to the orbital motion of a binary system. However, it is difficult to observe the cool star absorption lines at high enough resolution. The narrow FeI lines are rather weak and frequently masked in the blue-yellow region by the hot continuum. In many symbiotics, the radial velocity is close to zero, but a high velocity of about -140 km s^{-1} was found in AG Dra (Roman, 1953), which, together with its high galactic latitude, +41°, is strongly suggestive of a Pop II object. We should add that AG Dra is not unique for its high radial velocity. There are other cases in which the *emission lines* have high (positive or negative) radial velocity, which is probably associated with a high radial velocity of the system, rather than to the orbital motion of the components. For instance, a high radial velocity was found for the symbiotic novae V1016 Cyg (-68 km s^{-1}, FitzGerald and Pilavaki, 1974; Wallerstein et al., 1984); and RR Tel (-61 km s^{-1}, Thackeray, 1977). Large absolute values were also found in RT Ser (+92 km s^{-1}), AS 296 (+100 km s^{-1}), EG And (-95 km s^{-1}), and AX Per (-109 km s^{-1}) (Wallerstein, 1981; see also Section X). In CH Cyg, the radial velocity of the photospheric absorption lines and of the FeII, [FeII], and [OI] emissions is variable (Faraggiana and Hack, 1971), but the average value of -60 km s^{-1} is again very different from the local standard of rest. Wallerstein (1981) assembled the radial velocity of 19 symbiotic stars, and found a large velocity dispersion of 63±14 km s^{-1} (or 51±14 km s^{-1}, if AG Dra is omitted), similar to that of an old disk population such as long-period variables.

A systematic variability of the M-type absorption lines was found by Thackeray and Hutchings (1974) for the eclipsing symbiotic AR Pav, with a period in agreement with the period of the eclipses. A similar result was obtained by Hutchings et al. (1975) from the study of the cool star photospheric lines in AG Peg. More recently, Garcia (1986) performed a systematic study of the radial velocity in a number of symbiotic stars, using a cross-correlation technique. He found a periodic variation in AG Dra, EG And, T CrB, TX CVn, and RW Hya. This result has been confirmed by Garcia and Kenyon (1988; see Figure 11-14).

Presently, many observational programs are devoted to this crucial point, and there is growing evidence of periodic radial velocity variability in many symbiotic stars (see Section X).

IV.F. MAGNETIC FIELDS

The eruptive character of symbiotic stars might suggest the presence of intense surface activity in their dominant (= cool) spectral component. This, in turn, could be associated with the presence of strong magnetic fields. These fields should be variable according to their "activity," to possible stellar rotation and to different line-of-sight observations during the orbital motion, if the symbiotic object is binary. In the latter case, the hotter component could be a white dwarf, and these stars frequently have very intense magnetic fields. The search for magnetic fields and their time variability, in symbiotic stars, is therefore of no small importance in order to provide crucial information on the nature of the components. At present, however, the results are quite scanty and controversial, and further work is needed in the field. Two symbiotic stars—EG And and AG Peg—were included in the pioneering survey of Babcock (1958). Magnetic measurements in the blue spectral region of these two stars during 1949-55 gave a strong and variable magnetic field, with extreme values ranging from -1050 to +1100 gauss for EG And and from -1800 to +300 gauss for AG Peg. Babcock also noted that appreciable changes occurred in a few weeks.

Slovak (1982a) observed again the two symbiotic stars in 1978 with a photoelectric Zeeman analyzer measuring two spectral regions centered at 6129 and 6555 A; the first region contains many absorption lines, while the second includes Hα with emission and absorption components. Slovak did not confirm the kilogauss fields of Babcock, and provided a mean magnetic field of -3±49 and -66±36 gauss for EG And and AG Peg, respectively. He also noted a lack of magnetic line broadening in the two stars. Observations of

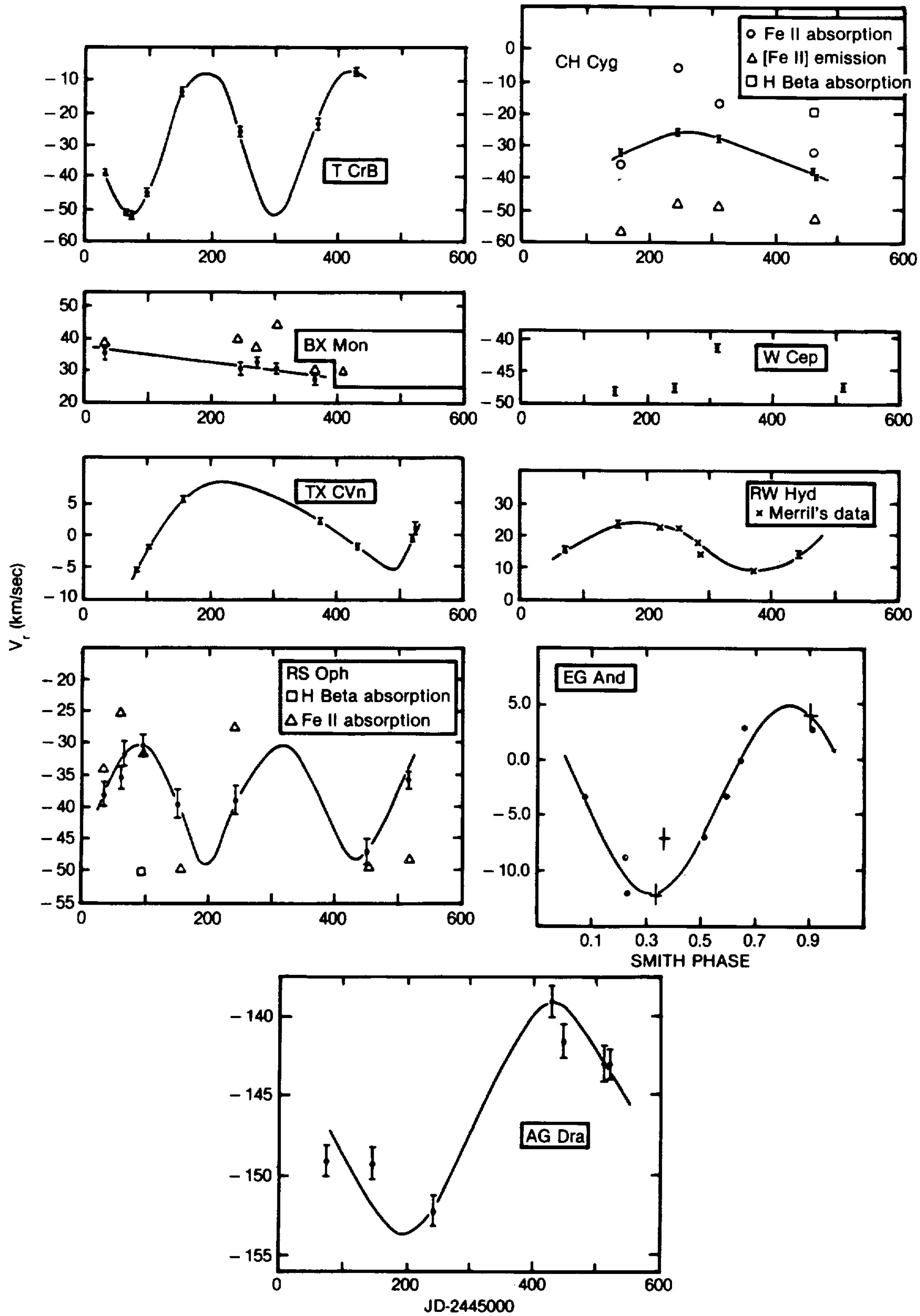


Figure 11-14. The radial velocity curves in symbiotic stars (Garcia and Kenyon 1988).

AG Peg separated by about one year do not give evidence of significant field variability in disagreement with Babcock results. Slovak also observed CH Cyg in 1978 and 1979 during its bright (V=6-7) phase, and again found a null result (+23±132 gauss, and no significant magnetic broadening in any of his spectra).

Luud (1986) discussed the results of Babcock and Slovak, which were based on measurements in two different spectral regions. The disagreement could then be related to the fact that two different physical regions were actually observed. Luud noted that the large (~ 10^3 gauss) magnetic fields of Babcock were observed close to the phase zero (hot star behind the red giant) of the orbital motion, just before ingress for EG And, and just after egress for AG Peg. Intense magnetic fields could be present in symbiotic stars only at certain phases of their orbital motion and of their activity. Therefore, future work should cover a period of several years to unveil this problem.

V. POLARIZATION

Polarization of the stellar radiation is, in general, an indication of deviation from spherical symmetry. Linear polarization has been measured in many stars surrounded by extended atmospheric envelopes and circumstellar matter, such as WR and Be stars, T Tau stars, novae and luminous red variables, as well as in some interacting binaries. Therefore, it is to be expected that also symbiotic stars should present a significant amount of polarization, since their spectral features clearly suggest the presence in most of them of extended, asymmetric atmospheres, of dusty circumstellar envelopes, disks, etc. This polarization should be variable with time according to the activity of the star, and/or to the orbital phase, and the study of its time variability should give precious information about the structure of the stellar envelope(s), as well as a better insight into their suggested binary nature. Symbiotic stars however, are, in general, rather faint in the visual, so that it is difficult to achieve a high enough accuracy in the polarimetric measurements. In addition, these objects are normally reddened by a significant amount of interstellar extinction, and in some cases, the intrinsic component of the polarization cannot be distinguished from the larger interstellar polarization, especially in the absence of variability. Only in very recent years has systematic polarimetry of symbiotic stars been undertaken, and still the amount of observations is too spare (at the time of writing this report) to draw clear conclusions on the polarization properties of symbiotic stars. An overview of the problem was recently given by Magalhaes (1988).

CH Cyg is one of the best studied symbiotic stars, being one of the brightest objects. This star, which is described in detail in Chapter 13, has an M6III spectrum and a variable blue continuum which fills the M photospheric absorption lines, and extends to the space ultraviolet (Hack and Selvelli 1982). CH Cyg was at minimum luminosity (about V=8) until the end of 1976, then brightened to V=7 in 1977 and to V=6 in 1981. A sudden drop of luminosity of one magnitude occurred in July 1984, then in 1985 the star faded to the preoutburst minimum of V=8.

Broad band polarimetry of CH Cyg was made throughout the whole recent light history. Rodriguez (1988) found that during the preoutburst phase, the degree of polarization was maximum in the blue (nearly 2 *per cent*), decreasing to 0.5 *per cent* in the red. A polarization increase was noted between 1974 and 1976 with a change of the position angle (Figure 11-15). Piirola (1982, 1983) measured the linear polarization of CH Cyg in the UBVRI bands during 1977-82, during the gradual brightening of the star. In 1978, the polarimetry in the UBV bands was again characterized by a larger polarization towards shorter wavelengths, with nearly constant position angle. After 1979, a different wavelength dependence was found with a strong rotation of the position angle with wavelength. Later, the blue-UV polarization decreased, but it was still larger than in the visual, where there was a minimum of polarization and an increase towards the red-near infrared. In 1981, the polarization in the longer wavelengths decreased, and the maximum polarization was in the blue. Rodriguez (1988) observed CH Cyg in September-October 1984 just after the luminosity drop: He measured a large decrease of the degree of polarization and a weaker dependence on wavelength than before (Figure 11-15). This peculiar behavior of CH Cyg can be explained by strong changes in the structure and geometry of the scattering envelope(s). In particular, the increase of the polarization of CH Cyg in 1980 in the R and I bands could be attributed to the presence of large ($a\sim$ 1μm) particles (Piirola, 1983), while the 1984 decrease should be caused by the contribution of the hot radiation source (Rodriguez, 1988).

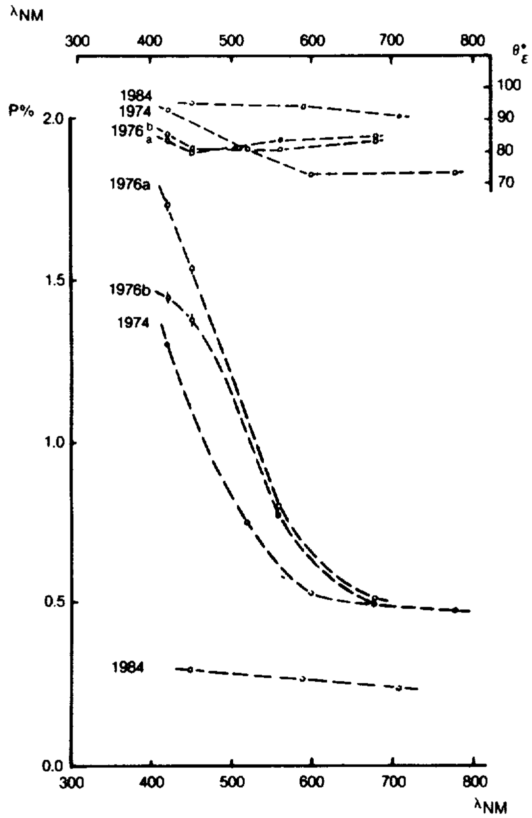


Figure 11-15. Linear polarization measurements of CH Cyg in 1974, 1976, and 1984 (Rodriguez, 1988).

The polarization of the symbiotic Mira R Aqr has been widely studied by several authors. This star is interesting for its relative nearness and for the many peculiarities, which will be discussed in detail in Chapter 13. Serkowski (1970) studied the time variability of the linear polarization of this star during the cycle of the Mira variable, and found large variations that suggest modulation of the structure of the circumstellar envelope by the Mira pulsation. He also found a large increase of the polarization towards the near ultraviolet. More recently, Aspin et al. (1985) discovered a remarkable structure of the polarization in the optical spectrum of R Aqr. The polarization increases across the TiO absorption bands and decreases in the emission lines (Figure 11-16).

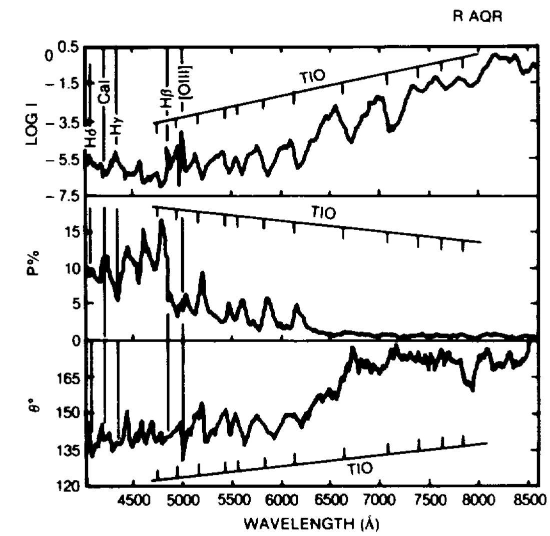


Figure 11-16. Intensity and polarization spectra in the Mira-type symbiotic R Aqr (Aspin et al., 1985).

CH Cyg and R Aqr are affected by a small amount of interstellar reddening (see Table 11-7), so that the linear polarization in these objects arises in the symbiotic system. Other symbiotic stars like CI Cyg are significantly reddened. In the eclipsing binary CI Cyg, the polarization appeared variable and was characterized by a strong rotation of the position angle with wavelength (Figure 11-17), which gives a clear evidence of the presence of an intrinsic polarization.

In general, the interstellar polarization could be quite large, but, since the observed polarization is the *vectorial sum* of intrinsic and interstellar polarization the stellar component can still be determined even if it is smaller than the interstellar one, in the case that the intrinsic and interstellar components are nearly orthogonal. The latter can be measured in nearby stars, which have no intrinsic polarization, and can be vectorially subtracted from the polarization measured in the symbiotic star.

Extensive polarimetry of symbiotic stars has been recently performed by Schulte-Ladbeck (1985) and Schulte-Ladbeck and Magalhaes (1986) (Figure 11-18). Some results of those observations are summarized in Table 11-3. It has

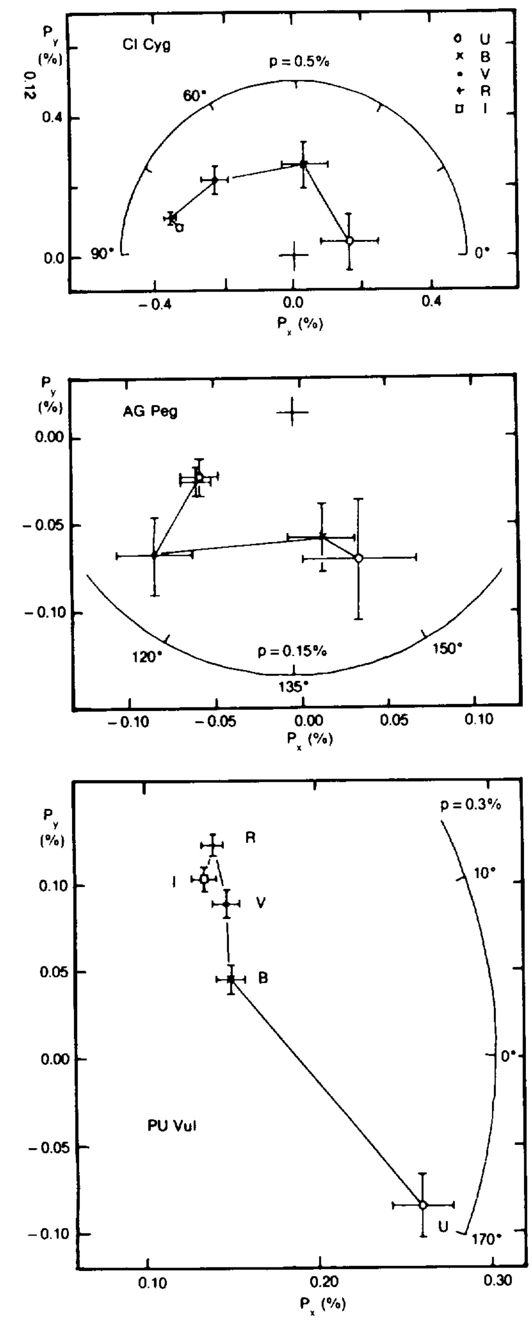


Figure 11-17. The wavelength dependence of the linear polarization in CI Cyg, AG Peg, and PU Vul (Piirola, 1983).

been found that some stars, namely V1016 Cyg, AS 338, and HM Sge, possess intrinsic polarization, while for the majority of the symbiotic stars, the observed polarization is interstellar. In general, the amount and nature of the polarization in symbiotic stars is not well known. In addition, nothing is known about the polarization near the emission lines and in the IR, and on the circular polarization. New extensive polarimetry of symbiotic stars is needed to gain precious information about their nature.

VI. INFRARED OBSERVATIONS

The first systematic infrared observations of symbiotic stars (e.g., Stein et al., 1969; Swings and Allen, 1972) revealed the presence of strong fluxes, which can be attributed to a cool component with a temperature around 3,000 K or less, and to circumstellar dust. Since then, a large amount of IR data on these objects has been accumulated also thanks to space observations with the IRAS satellite. These data are providing a fundamental ground for understanding the nature of the cool components of the symbiotic systems. They represent a real progress on the study of the symbiotic phenomenon, as is illustrated below. Two main categories of symbiotic stars were clearly identified, thanks the IR observations: the S- and D-type systems, which are characterized by different energy distribution and time behavior. (Actually, there is another category, or subgroup of symbiotic stars called D'-type, which significantly differ from the D-type objects).

The discovery of this *bimodal distribution* of symbiotic stars in the near-IR has been one fundamental step to understand the nature of the symbiotic phenomenon. In particular this IR behavior is correlated with properties of the stars at other wavelengths. It has also been noted that the D-type systems have, in general, a higher level of excitation of the emission line spectrum. In the following sections we shall discuss the energy distribution and the main spectral features of these groups and analyze their time behavior.

VI.A. ENERGY DISTRIBUTION

The infrared observations of symbiotic stars have proved to be a fundamental tool to investigate the nature of these objects. The first IR observations of symbiotic stars were made by Swings and Allen (1972), who found that these objects have color indices similar to those of late-type stars. Later on, Webster and Allen (1975) recognized the presence among symbiotics of two

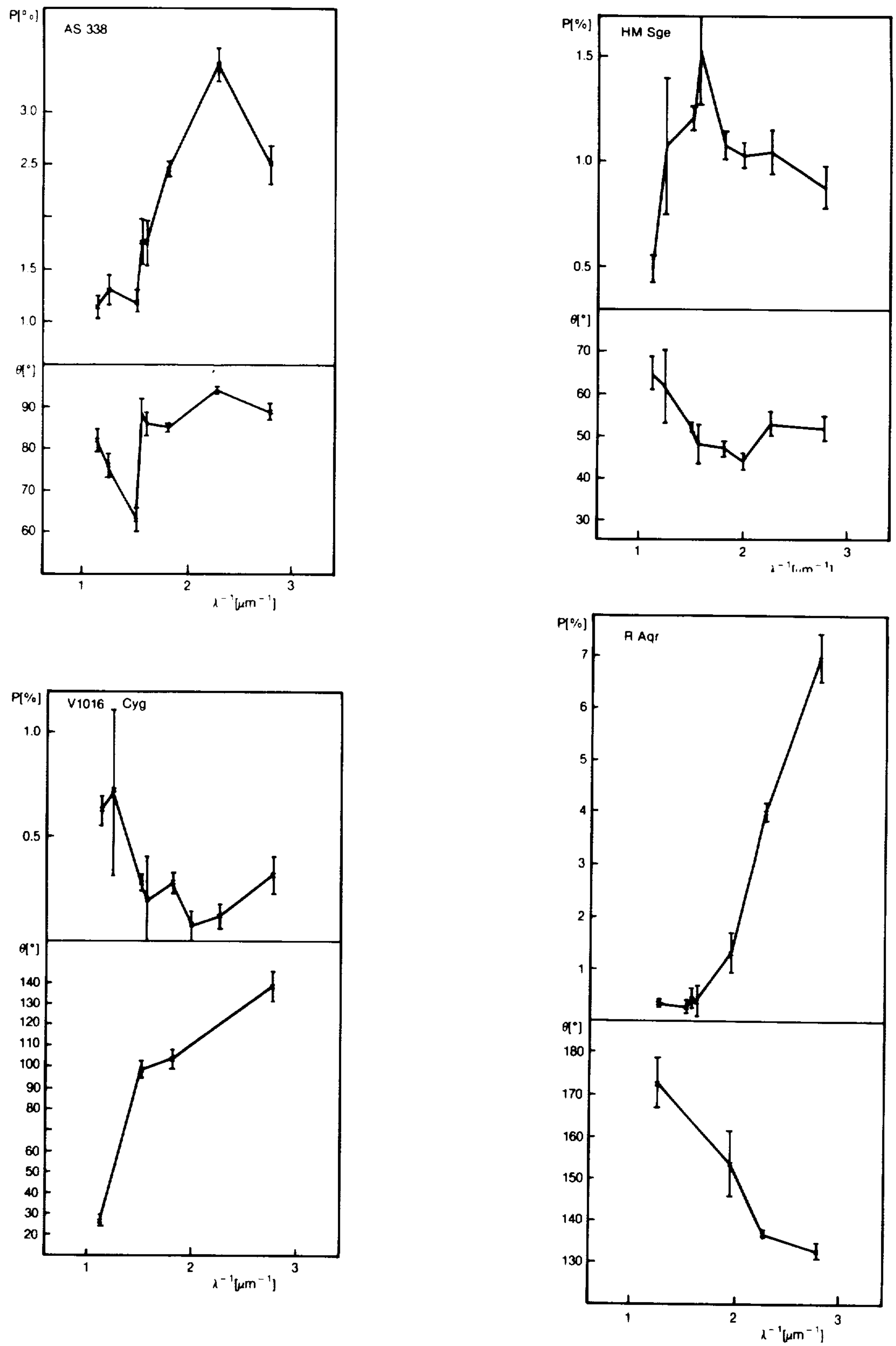


Figure 11-18. The wavelength dependence of the linear polarization in some symbiotic stars (Schulte-Ladbeck 1985).

TABLE 11-3. LINEAR POLARIZATION IN SYMBIOTIC STARS.

Object	Sp	IR	Polarization (P,θ)			Remarks
			1.5μm⁻¹	2.5 μm⁻¹	3. μm⁻¹	
R Aqr	M7	D		4.02,137°		var,7,8,3,4
CH Cyg	M6	S	0.2-0.5	0.3-1.8	1.3-2.0	var,5,6
CI Cyg	M4	S	0.3,81°	0.5,95°	0.7,153°	8,9
			0.43,90°		0.33,	7
			0.3,70°	0.25,40°	0.15, 5°	5
V1016 Cyg	M	D	0.28,104°	0.12 -		7
AG Peg	M2	S	0.1,115°	0.07,140°	0.10, 117°	5
RX Pup	M	D	1.8,123°	1.9, 118°	1.65, 113°)	1
HM Sge	M	D	1.08,47°	1.05, 53°		2,7
PU Vul	F+M	S	0.13	0.15	0.3	5
AS 338	M5	S	2.46,85°	3.44,94°		7

References: (1) Barbier and Swings (1982); (2) Efimov 1979); (3) McCall and Hough (1980); (4) Nikitin and Khudyakova (1979); (5) Piirola (1982, 1983); (6) Rodriguez (1988); (7) Schulte-Ladbeck (1985), (8) Serkowski (1970); (9) Szkody et al. (1982).

groups of objects with different energy distribution, the S- and D-type symbiotic stars. The general behavior of the two categories is described in detail by Allen (1979, 1982).

Figure 11-19 shows the near-IR energy distribution of a number of symbiotic stars. Some ob-

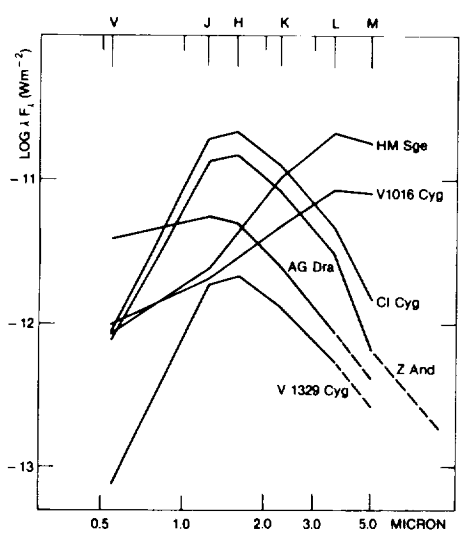


Figure 11-19. The visual-near infrared energy spectrum of some symbiotic stars (Eiroa et al., 1982). Two separate categories of objects are recognized showing respectively a maximum in the near-IR (the so-called S-type symbiotics) or a gradual rise to the mid-IR (the D-type ones).

jects, such as Z And and CI Cyg, present a sharp rise from the visual to the near-IR with a broad maximum at 1-2 μm, and a gradual slope at longer wavelengths. This is the typical IR spectrum of the S-type symbiotic stars. In the two-color diagram (Figure 11-20), these stars are grouped near the locus of the late-type stars with J-H = ~ +0.8 to +1.5 and H-K= ~ +0.2 to +0.5 (Allen, 1982). This fact is immediately interpreted as due to the presence of a late star— typically an M giant—in the S-type symbiotics, and several authors succeeded in fitting their energy distribution from the visual (if not affected by the hot continuum and the emission lines) to the mid-IR with the spectrum of normal late-type stars (e.g., Kenyon et al., 1986; Viotti et al., 1986). As discussed below, the far-IR observations with the IRAS satellite have given a further support to this interpretation.

A different behavior is displayed by the so-called D-type symbiotics. These objects represent a rather small subgroup, being about 20 *percent* of the total in current catalogs of symbiotic stars. Typical members of this subgroup are RR Tel, V1016 Cyg, HM Sge, and RX Pup. Their red continua have a smaller slope than in the S-type symbiotics, but the energy distribution peaks at longer wavelengths and is much redder than in normal M-type stars (Figure 11-

19). The H-K color index ranges from +0.5 to +1.8 (Allen, 1982; Figure 11-20). These values are characteristic of objects such as carbon stars and highly reddened nebular objects, where the extreme red color is attributed to a large intrinsic reddening and to thermal emission from circumstellar dust. Actually, the IR excess in the D-type symbiotics is commonly interpreted as due to dust emission, hence the name "D." However, it should be considered that, in general, it is difficult to fit the observed near-IR spectrum with a single temperature component.

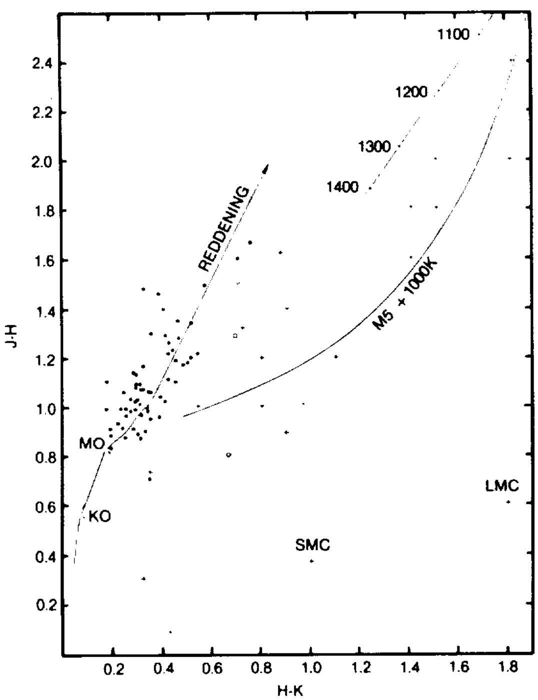


Figure 11-20. The two-color IR diagram for the symbiotic stars (Allen 1982).

A small number of symbiotics have a large excess longwards of 2-3 μm. Their IR energy distribution suggests a lower color temperature than in D-type symbiotics. Generally, the optical spectra are earlier than in other objects, F- or G-type, and were called by Glass and Webster (1973) as "yellow symbiotics." Allen (1982) defined these systems as D'-type symbiotic stars. Some examples are M1-2, AS 201 and HD 149427.

A new insight on the problem of symbiotic stars was recently provided by the IRAS observations (IRAS, 1985). Kenyon et al. (1988) reported that 34 S-type and 28 D-type objects were successfully detected. The frequency of D-type systems is thus larger than in the catalogs, as expected from their larger IR excesses. Four D-type symbiotics—R Aqr, V471 Per, RR Tel, and AS 201—were also detected at 100 μm. Because of their far-IR weak fluxes, only a few S-type systems were detected at 25 and 60 μm. A particularly interesting case is EG And. This star is rather faint in the IR, but has the chance of being placed close to M31, the Andromeda galaxy. Since IRAS has accumulated a long observing time for the galaxy, the limiting flux for IR sources in the field, including EG And, is much lower than in the IRAS Point Source Catalogue. The detected fluxes of EG And were: 4.6, 1.2, and 0.23 Jy at 12, 25, and 60 μm, respectively, while there is an upper limit of 0.7 Jy at 100 μm (Kenyon et al., 1986; 1988).

In the IRAS two-color diagram (Whitelock, 1987; 1988; Kenyon et al., 1988), the S-type systems are placed in a rather limited locus, close to cool stars, while the D-type systems are distributed in a large region of the HR diagram, including the loci of the Mira variables and of the planetary nebulae (see also Persi et al., 1987).

The IR energy distribution of the best observed S- and D-type symbiotics, based on ground and space (IRAS) observations is depicted in Figure 11-21. The mid-IR of the S-type systems is close to the Rayleigh-Jeans tail of the cool star spectrum with a modest or no indication of far-IR excess due to dust emission. This result is confirmed by the detailed study of the IRAS data by Kenyon et al. (1988). The large mid-IR excess of the D-type systems, in principle, would imply the presence of a strong thermal dust emission (e.g., Allen 1982). Circumstellar dust should be heated by the stellar photons (more probably, from the cool giant) at a temperature around 10^3 K. But Kenyon et al. (1986) suggested that in these systems the cool component, the giant star, is heavily reddened ($A_k \sim 1$-2) by dense circumstellar dust envelope. In this case, the observed spectrum is not thermal dust emission, but instead the reddened cool giant spectrum.

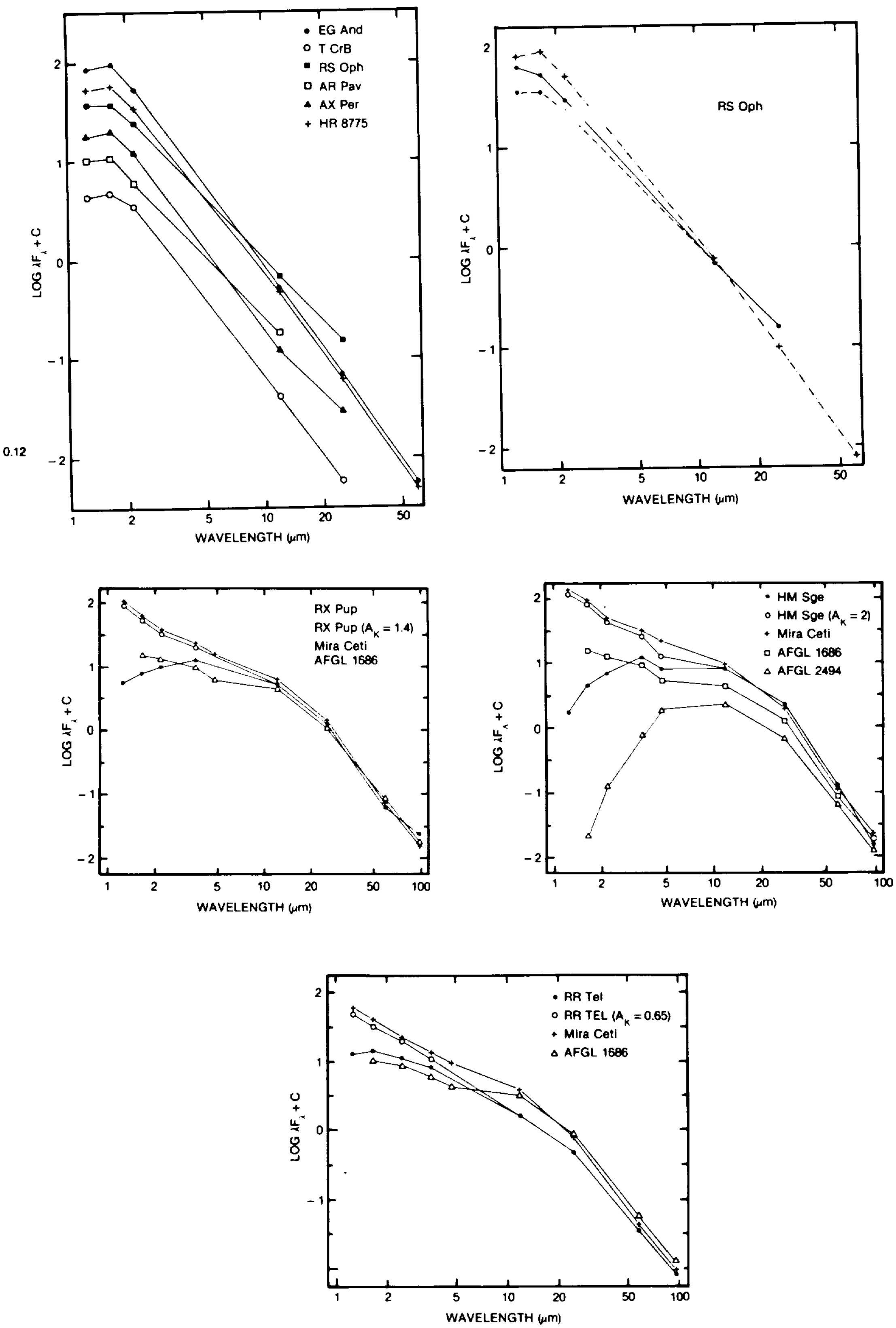


Figure 11-21. The infrared energy distribution of S-type (a) and D-type (b) symbiotic systems (Kenyon et al., 1986).

VI.B. SPECTRAL FEATURES

The major spectral features in the near-IR spectra of late-type giants and supergiants are the CO and H_2O absorption bands at 1.6, 2.3, 4.7 μm and 1.4, 1.9, 2.7 μm, respectively. The strength of these features depends on the temperature and luminosity of the cool star, and can thus be used to classify the cool components of the symbiotic systems and ultimately to derive their distance. CO and steam absorption features have been observed in several symbiotic stars. Kenyon and Gallagher (1983) have investigated the low-resolution IR spectra of symbiotic stars and find evidence of the 2.3 μm CO band in 12 S-type symbiotics and in R Aqr. By comparison with normal M-stars, Kenyon and Gallagher have derived the basic properties (temperature, luminosity, and distance) of the cool components for a number of symbiotic stars.

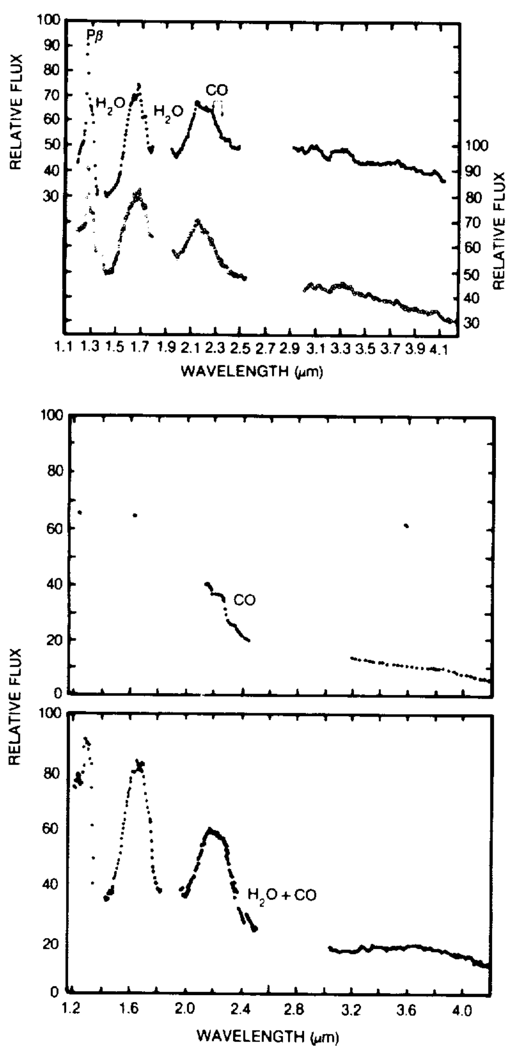


Figure 11-22. The near-infrared spectrum of symbiotic stars (Whitelock et al., 1983a).

Since TiO bands have been identified in the optical spectra of these stars, the IR provides a further proof of the presence of a late-type star, whose energy spectrum is the dominant contributor to the red-near IR spectrum of S-type symbiotics. Another evidence is provided by the Mira-type IR pulsation as discussed below. We should finally recall that the 2.3 μm CO band was observed in emission in the Mira-type symbiotic BI Cru (Whitelock et al., 1983c).

VI.C. VARIABILITY

Another important distinguishing feature of D-type symbiotics is their large IR variability. First, Harvey (1974) discovered that V1016 Cyg presented a long-time scale variation in all the IR photometric bands, from 1.2 to 10 μm, with a maximum amplitude of about 1 magnitude at K and of $1^m.5$ at H. This result should provide a direct evidence for the presence of a Mira-type variable star in V1016 Cyg. Harvey's work has, in the meantime, shown the importance for a continuous monitoring of symbiotic stars, which should give important information on the nature of the cool component. However, we had to wait almost one decade to have a real progress in this problem.

In fact, systematic photometry of southern symbiotic stars, especially at the South Africa Observatory, led to the discovery of large amplitude periodic variations in the IR of D-type symbiotics: RR Tel (Feast et al., 1983a), RX Pup (Whitelock et al., 1983a), and in the similar Mira system R Aqr (Whitelock et al. 1983b). Feast et al. (1983b) also found Mira-type variability in three more D-type systems: He2-106, He2-38, and He2-34. Some typical light curves are shown in Figure 11-23. As far as the northern systems are concerned, Taranova and Yudin (1983) confirmed the Mira-type variability in V1016 Cyg

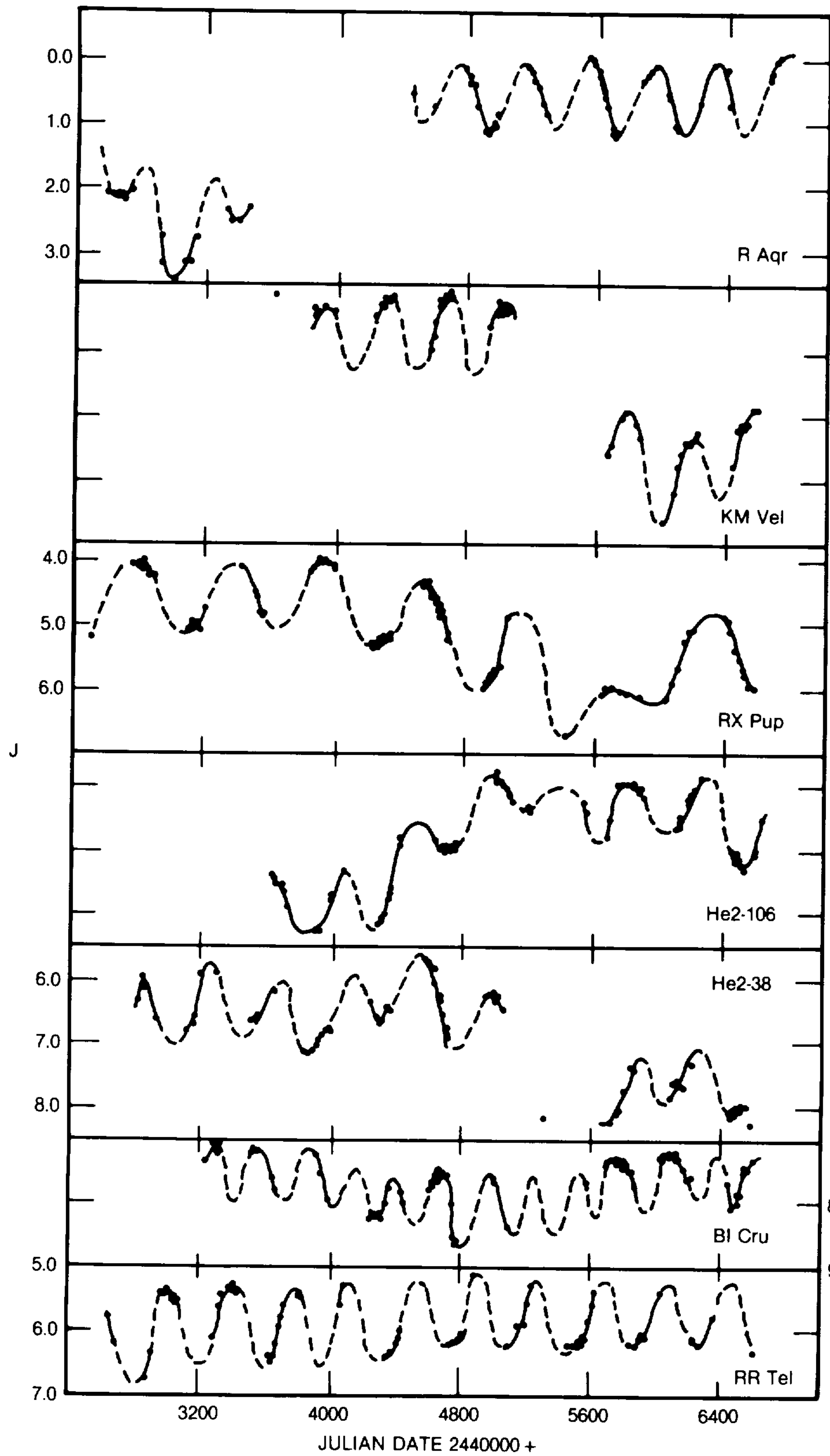


Figure 11-23. The infrared variability of Mira (D)-type symbiotic stars (Whitelock, 1987).

and found similar amplitude and time scale in HM Sge. The periods and amplitudes of the IR variability are summarized in Table 11-4. The derived periods range from about 300 to 600 days and correspond to the long-period Miras, which also have larger amplitudes in the IR (see Feast et al., 1982). These periods are of the same order of magnitude of the orbital periods observed or expected for the symbiotic systems. Thus, care should be taken to recognize the different nature of the two kinds of periodic variability.

A long-time scale trend has been found for the IR maximum luminosity in R Aqr, RX Pup, He2-34 and He2-106, which could be explained by variable dust obscuration (Feast et al., 1983b; Whitelock et al., 1983a).

In the S-type symbiotic systems the IR variability is generally of smaller amplitude and irregular. Systematic observations of the northern objects have been especially undertaken by O.G. Taranova and B.F. Yudin in Crimea (e.g., Taranova and Yudin, 1983). In this regard, it should be remembered that all M giants and supergiants later than M4 are variable. The IR variability of the stellar-type symbiotics is thus not unusual, but confirms the rule and shows again that their cool components behave like a normal single star.

Finally, we recall that most of the above observations have been made during quiescent phases of the symbiotic stars. It is also important to study the behavior during an active phase and to look for possible correlations. In fact, some models for symbiotic stars assume that the cool star activity, possibly associated with an increased rate of mass transfer to the dwarf companion, could be responsible for the observed symbiotic activity. Both the classical symbiotic stars Z And and AG Dra underwent outbursts in recent times, and are suitable for considering more thoroughly this problem. The IR photometry of these events led to the conclusion that no large change of the IR spectrum occurred during the outbursts (Cassatella et al., 1984; Viotti et al., 1985; Cassatella et al., 1988a). A similar result was found for the symbiotic nova PU Vul. This star, after its 1978 outburst, suffered a deep luminosity fading in 1980. Simultaneous ultraviolet

TABLE 11-4. INFRARED VARIABILITY OF SYMBIOTIC STARS.

Object	ΔJ (mag)	ΔK (mag)	T(days)	Ref.
D-type symbiotic stars				
V1016 Cyg	1.0	1.0	450	1,2
BI Cru	1.0	0.8	280	3
RX Pup	1.2	1.0	580	4
HM Sge	1.2	1.5	500:	2
RR TEL	1.5	1.0	387	5
He 2-34	0.8	0.5	370	3
He 2-38	1.0	0.8	433	3
He 2-106	1.5	0.9	400	3
S-type symbiotic stars				
Z And	0.2:	0.3:	=	6
CI Cyg	0.5:	0.5:	=	6,7
AG Peg	0.2	0.1	=	8
Related objects				
R Aqr	1.0	0.8	387	9

References: 1. Harvey (1974). 2. Taranova and Yudin (1983). 3. Feast et al. (1983b). 4. Whitelock et al. (1983b). 5. Feast et al. (1983a). 6. Taranova and Yudin (1981). 7. Baratta and Viotti (1983). 8. Feast et al. (1983b). 9. Whitelock et al. (1983a).

and infrared observations made by Friedjung et al. (1984) showed that while the ultraviolet flux largely decreased during the minimum, the infrared remained nearly the same, indicating that the source of the IR radiation (the cool giant) was not affected by the event. The amount of IR observations of symbiotic stars during outburst is still poor to make a general conclusion. But all the above results are in favor of a cool component that is not directly involved in the symbiotic activity. Actually, the observed IR variability seems to be a peculiarity of the cool component, not necessarily associated with the symbiotic phenomena.

VII. RADIO OBSERVATIONS

VII.A. INTRODUCTION

Radio observations provide a probe of the large scale structures from a few stellar radii to the typical sizes of planetary nebulae. It is therefore a useful tool to investigate stellar winds, accretion structures, and ejecta. Symbiotic objects generally are weak radio emitters. Thus, a significant progress in this field was made only when large area radio telescopes began to be available. A comprehensive summary of the radio observations of symbiotic stars can be found in the book on Radio Stars (Hjellming and Gibson, 1985). The first object successfully detected at radio wavelengths was V1329 Cyg (HBV 475), which was pointed by the 100 m MPI Bonn radio telescope in October 1972 at 10.63 Ghz (Altenhoff and Wendker, 1973). This star is known for having brightened in 1966. A rather weak flux (~ 10mJy; 1 Jy=1.10^{-26} watt m^{-2} Hz^{-1}) was detected in this star known to have exploded in 1967. A larger flux was found by Purton et al. (1973) in another symbiotic nova, V1016 Cyg, which exploded in 1964. This latter observation is of particular importance, not only for the large impact of radio observations on the understanding the symbiotic phenomenon, but more in general for the modelling of stars with optically thick winds. In fact, after the first detection of V1016 Cyg at 10.63 Ghz, observations at other frequencies, from 26.95 to 10.70 Ghz, revealed that the radio spectrum was remarkably linear, with a mean slope of about 0.75, a value significantly smaller than the value of 2.0 expected for a uniform slab of optically thick gas emitting by the free-free process, and larger than the optically thin case, which is nearly independent of the frequency. Figure 11-24 shows the radio spectrum of V1016 Cyg.

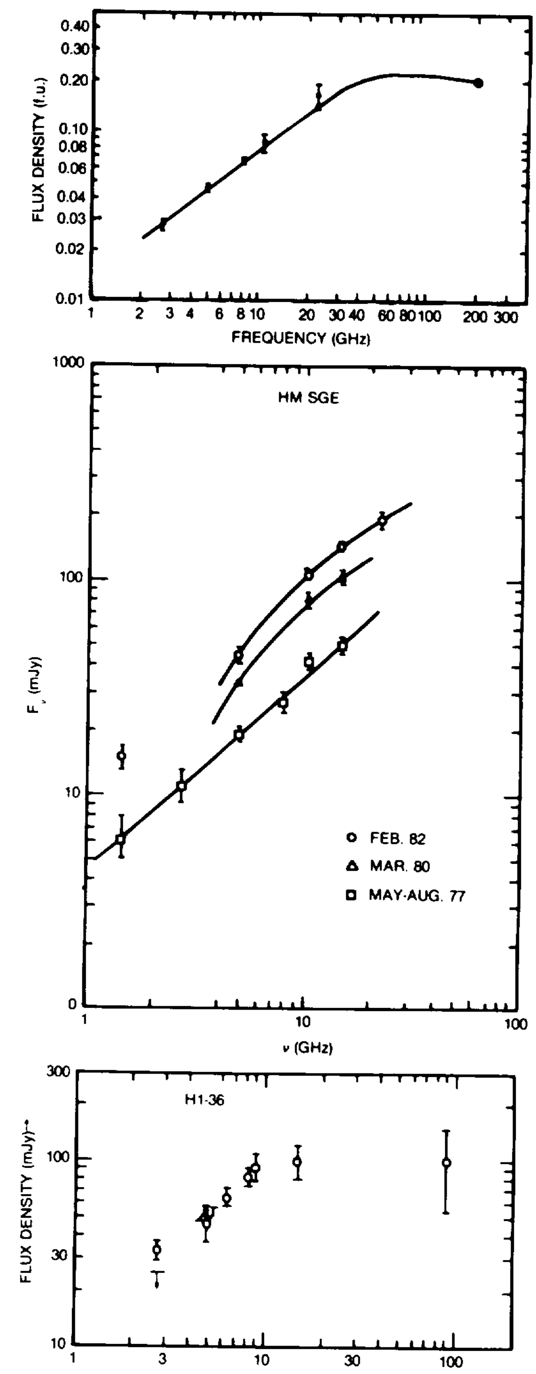


Figure 11-24. The radio spectrum of symbiotic stars. (a) V 1016 Cyg (Marsh et al., 1976); (b) HM Sge at different epochs after its 1975 outburst (Kwok et al., 1984); (c) HI-36 (Purton et al., 1977).

Seaquist and Gregory (1973) found that the observed slopes rather support a model in which the central object is undergoing a continuous mass ejection (i.e., it has a stellar wind). Therefore, the radio flux at a given frequency provides a measure of the mass-loss rate (under certain assumptions about the electron temperature and the structure of the wind, and if the distance is known). The model of an optically thick (at radio wavelengths) ionized wind from a hot central star was later developed by Panagia and Felli (1975) and Wright and Barlow (1975).

Following the first observations of V1329 Cyg and V1016 Cyg, several symbiotic stars were pointed to with radio telescopes, with varying (positive and negative detection) results. For instance, Wendker et al. (1973) failed to detect AG Peg and Z And, while intense radio emission was found from the D-type symbiotic nova HM Sge two years after its outburst, which is continuously rising (Purton et al., 1982). An extensive radio survey of Wright and Allen (1978) of 91 targets led to the discovery (or confirmation) of only 9 sources, all but one (AG Peg) belonging to the D-type subgroup discussed in the previous Section VI. A particularly intense flux was found for HM Sge, RR Tel, and H1-36, which is the most intense one (91 mJy at 14.5 and 8.9 Ghz). Wright and Allen also found a clear correlation between the 14.5 Ghz flux and the dust emission at 10 μm. This is shown in Figure 11-25.

The opening of the Very Large Array (VLA) radio telescope of Socorro, New Mexico, in 1981 afforded the opportunity of a basic improvement of our knowledge of radio emission from symbiotic stars. A survey of 59 symbiotic stars at 4.9 Ghz was carried out by Seaquist et al. (1984) who found 17 positive detections, including several S-type systems not observed before. A compendium of the radio observations at 6 cm (4.9 Ghz) from different sources is given in Table 11-5. In general D-type systems have stronger radio emission than the S-type ones. It is, however, difficult to find an immediate interpretation of this result, since it could be affected by unknown selection effects, and obviously by the uncertainty on the distance.

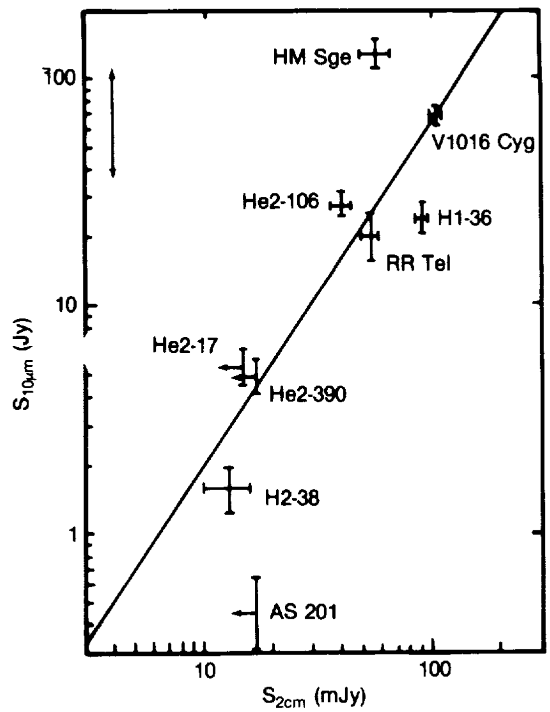


Figure 11-25. The radio flux at 14.5 Ghz versus the 10 μm emissions in D-type symbiotic stars (Wright and Allen, 1978).

VII.B. RADIO VARIABILITY

A few objects have been repetitively observed over a long time interval, and this could provide information about the long-term variability and possible correlation with the optical behavior. After its first detection, V1329 Cyg was irregularly observed at radio wavelengths for several years. During 1972 to 1978, its radio flux probably remained at a nearly constant flux of 12-14 mJy at 10.7 Ghz (Purton et al., 1982). The star was not detected at 4.89 Ghz in 1980 (Kwok et al., 1981), while two years later Seaquist et al. (1984) reported a flux level of 2.16±0.44 mJy at the same frequency. It should be considered that the 1980 radio observation was made near a luminosity maximum of the star (phase 0.48, according to the Iijima (1981) parameters). At that phase, the emission line and UV continuum fluxes are at maximum (e.g., Nussbaumer and Schmutz, 1983). RX Pup is a D-type symbiotic characterized by a large radio variability, but with a still unknown time behavior (Seaquist and Taylor,

TABLE 11-5. 6 CM RADIO OBSERVATIONS OF SYMBIOTIC STARS

Object	Flux (mJy)	Slope (α)	Size(*) (arcsec)	Ref.
D-type symbiotics				
V1016 Cyg	61	+0.8	0.5	1,2
RX Pup	34 var	+0.72	0.50	3
HM Sge	40-90 var	+0.78	0.36x0.24	4
RR Tel	28			2
S-type symbiotics				
Z And	1.2	+0.62	<0.6	5
BF Cyg	2.1	+0.98	<0.7	5
CH Cyg	0.4-18 var	(see ref 6)	1.5	6
CI Cyg	<0.42			5
V1329 Cyg	2-5 var		<2.8	5,7
AG Dra	0.5			5,8
YY Her	<0.35			5
AG Peg	8.2		1.5	5
related objects:				
R Aqr	12.5	+0.6	100	11
RS Oph	20-82 var	(see ref 13)	0.2	12,13
RT Ser	1.3	+0.73		5
H1-36	46	+1.05	5.0	14

Notes to the table. (*) *Data on angular sizes (generally at 6 cm) are from Seaquist et al. (1984), Hjellming and Gibson (1985), and Taylor (1988).*

References: (1) *Purton et al. (1973).* (2) *Purton et al. (1982).* (3) *Seaquist and Taylor (1987).* (4) *Kwok et al. (1984).* (5) *Seaquist et al. (1984).* (6) *Taylor et al. (1986, 1988).* (7) *Altenhoff and Wendker (1973).* (8) *Torbett and Campbell (1987).* (11) *Hollis et al. (1985, 1987).* (12) *Padin et al. (1985).* (13) *Spoelstra et al. (1987).* (14) *Purton et al. (1977).*

1987). The D-type symbiotic nova V1016 Cyg was continuously monitored at 2.8 cm since 1973, but only marginal evidence of variation was found (Purton et al., 1981; Becker and White, 1985). The star may have reached a stationary stage after the 1964-66 outburst, and this is in agreement with the spectroscopic and photometric results. It must be noted that in 1969, M. B. Bell, E. R. Seaquist, and W. J. Webster failed to detect V1016 Cyg, with an upper limit of about 100 and 70 mJy at 4.6 and 11 cm, respectively (see FitzGerald and Houk, 1970). These upper limits are a factor of two larger than the radio fluxes detected later; thus, they cannot be used as an indication of a rise of the radio luminosity. Also, no variability was found in the strong source H1-36 (Allen, 1983). A different situation holds in the case of HM Sge, which underwent its outburst in 1975 and was first radio-detected in 1977. Since then, the star has been frequently monitored, and a gradual increase of the radio flux was found (see Figure 11-24 and Table 11-6). The radio spectrum remained optically thick over all the observed frequency range, and this fact provided means to estimate the expansion velocity of the optically thick surface (which is not necessarily the wind velocity) of about 100 km s^{-1} (Kwok, 1982). This time evolution can be compared to that of the recurrent nova RS Oph, which, after its 1982 outburst, rapidly increased its radio flux up to 63 mJy in a few weeks (Padin et al., 1985). The fact that no variability was found in the similar object V1016 Cyg has to be related to the more time elapsed since the outburst in the latter one. Thus, we expect HM Sge to reach a constant radio luminosity in few years. The radio variability in symbiotic objects is summarized in Table 11-6.

VII.C. RADIO IMAGERY

Radio observations have represented and for a long time will represent a unique way to make very high spatial resolution imagery of circumstellar envelopes of different categories of astrophysical objects. For instance, the Socorro radio telescope in its most extended (35 km) configuration can reach an angular resolution of 0.07" at 1.3 cm. This resolution is one order of magnitude larger than that achievable at optical wavelengths for diffuse sources. A few symbiotic objects have been so far observed at high spatial resolution, and the radio observations have disclosed quite a variety of structures, such as shells, halos, jets, and bipolar nebulae. A special case is the radio source associated with the Mira variable R Aqr which will be discussed in Chapter 13, which is devoted to the detailed discussion of this star. A description of the radio nebulae in symbiotic stars can be found in the volume Radio Stars (Hjellming and Gibson, 1985) and in Taylor (1988).

The radio emission from V1016 Cyg has been resolved into two lobes separated by about 0.10" in the NE-SW direction (Figure 11-26). As discussed above, this star has been considered the classical example of a radio source produced by thermal emission from a stellar wind (Seaquist and Gregory, 1973). These observations seem instead to suggest a rather different model, with ejection of matter preferentially in polar directions as in the bipolar nebulae. Such a radio structure can hardly be resolved in the optical region from ground-based telescopes. However, Solf

TABLE 11-6. RADIO VARIABILITY OF SYMBIOTIC STARS

Object	Date	Nu(Ghz)	Flux (mJy)	Reference
V1329 Cyg	1972.8	10.7	10 ± 2	1
....	1978:	4.9	5 ± 1	2
....	1980.2	4.9	<1.	3
....	1982.1	4.9	2.2 ± .4	3
HM Sge	1977.4	10.6	40	4
....	1980.3	10.6	80	4
....	1981.x	10.6	90	4
....	1983.8	4.9	51 ± 3	5
CH Cyg	1984.9	15.0	9.3	6
....	1985.1	15.0	25.8	6
....	1985.9	15.0	44.0	7
....	1986.2	15.0	24.3	7
....	1987.0	15.0	8.2	7
RS Oph	1982.1	5.	<0.32	3
....	1985.12-.17	5.	20 to 63	8,9
....	1987.18	5.	82	9
....	1985.17-.46	5.	59 to 22	9

Notes to the Table. (1) Altenhoff and Wendker (1973). (2) Hjellming (1981). (3) Seaquist et al. (1984). (4) Kwok et al. (1981). (5) Becker and White (1985). (6) Taylor et al. (1986). (7 Taylor et al. (1988. (8 Padin et al. (1985). (9) Spoelstra et al. (1987).

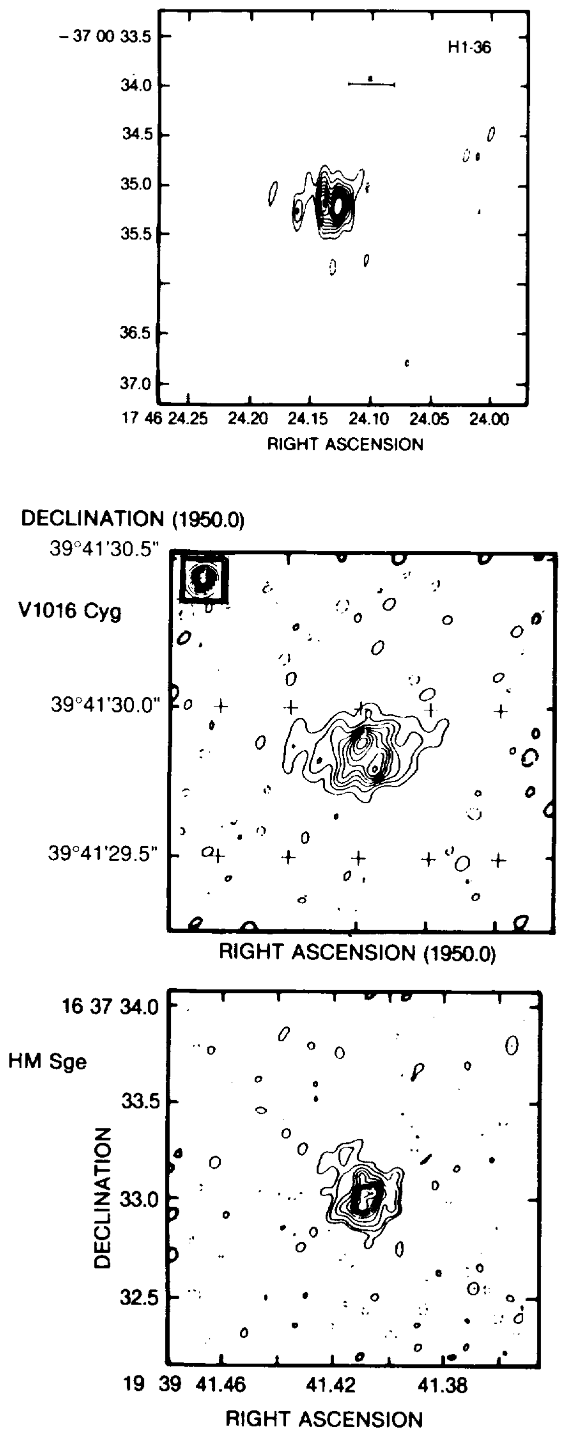


Figure 11-26. Radio images of symbiotic stars (Taylor, 1988).

(1983) succeeded in separating the two components of V 1016 Cyg, using high-spatial, high-spectral resolution observations near the [NII] 6583 A emission line.

The high-resolution radio image of HM Sge (Figure 11-26) shows a diffuse symmetrical emission, or *halo*, with a size of about 0.5" at 1.3 cm (22 Ghz), and a central bipolar structure similar to that of V1016 Cyg with an extension NS of 0.15. Both stars—HM Sge and V1016 Cyg— are known for their recent outburst, and for the peculiar bipolar radio structure. An even more complex structure is shown by the S-type symbiotic star AG Peg, in which three separate structures can be identified: a spherical nebulosity, a compact core (θ<0.1" at 15 Ghz), and a possible jet-like structure 0.8" long, extending from the central core through the halo (Figure 11-26). Like the previous two objects, AG Peg has also suffered a major nova-like outburst. The question is whether the present radio structure is associated with this behavior (see Viotti 1987a). Table 11-5 summarizes the maximum angular size at radio wavelengths of some symbiotic stars.

VII.D. THE RADIO OUTBURST OF CH CYGNI

CH Cyg represents a unique example of evolution of a radio nebula. This star recently underwent a radio outburst followed by the appearance of ejecta (Taylor et al., 1986). During April 1984 to May 1985, the radio flux increased by about a factor of 35, while VLA 2 cm observations on 8 November 1984 disclosed the presence of two radio knots separated by 0.18". Taylor et al. (1986) also found that 75 days later, the radio image evolved into a three-component structure with a total separation of 0.4" (Figure 11-27).

This radio outburst of CH Cyg was associated to a luminosity decline of the star of about 1.5 mag (Tomov, 1984). In the same time, Selvelli and Hack (1985) observed a dramatic increase of the line excitation in the ultraviolet. Taylor et al. (1986) explained the radio evolution of CH Cyg as the result of formation of ejecta, which are moving away from the central object at a very high speed, about 1.1 arsec/yr, corresponding to a projected velocity of about 1000 km s^{-1}. The thin lines in Figure 11-27 connect the corresponding knots according to this hypothesis. This conclusion also seems to be supported by the large width of the hydrogen lines. Thus, CH Cyg could

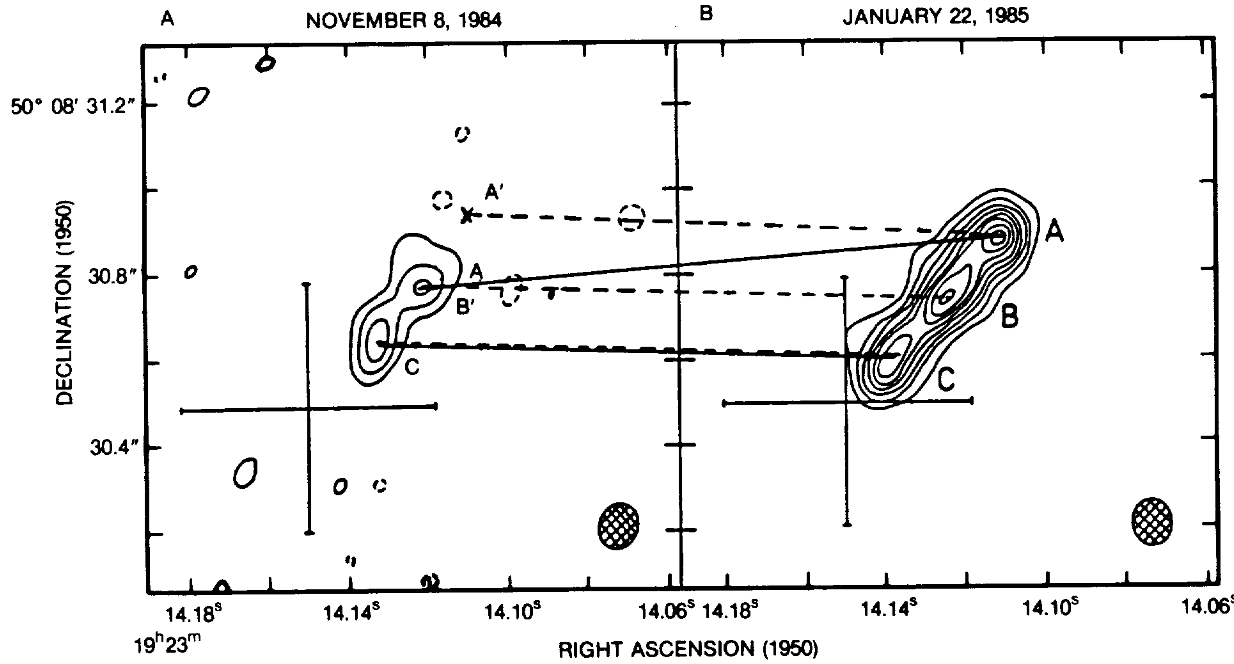
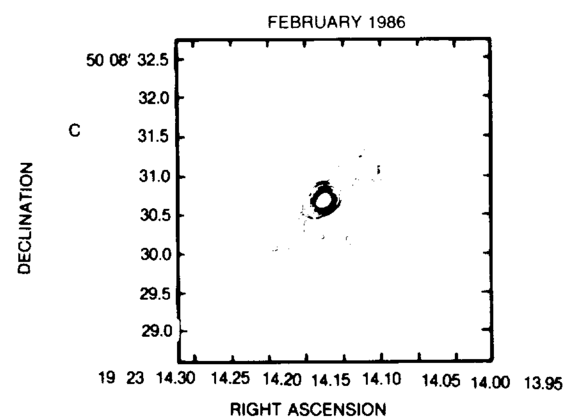


Figure 11-27. The radio map of CH Cyg after the 1984 radio outburst: (a) 8 November 1984; (b) 22 January 1985 (Taylor et al., 1986); (c) February 1986 (Taylor et al., 1988).



be considered as the best example of jet activity. There is , however, an alternative and simpler explanation of the observations: the two sources observed in November 1984 (labelled A and C in Figure 11-27a) would correspond not to the sources A and C of Figure 11-27b), but to B and C, respectively. This correspondence is indicated in the figure by dashed lines. In such a hypothesis the apparent motion of the radio structures, especially of knot A, would be much lower than that claimed by Taylor et al. (1988) and possibly equal to zero. Also, the broadness of the Lyα emission, shown in the following Figure 11-29, is more easily explained by a very large optical thickness so that the observed wings are the damping wings of the emission lines, rather than related to Doppler broadening. The appearance of the radio jets in CH Cyg could be associated with a sudden increase of the flux of ionizing photons from the central object in mid-1984, followed by the propagation of an ionizing front through the preexisting circumstellar matter. The increase of the line ionization in the UV and the detection of an X-ray emission (Leahy and Taylor, 1987) give further support to this intepretation.

VII.E. MASER EMISSION

The observation of radio lines of molecular species from late-type stars is an important tool to investigate their outer envelopes. Maser emission of OH, H_2O, and SiO has been detected at radio wavelengths in several objects, including M supergiants, carbon and S stars, and Mira variables (e.g., Lepine et al., 1978, and references therein). Most of the SiO sources are Mira variables, and there is evidence that most, if not all, Miras are SiO emitters. This maser emission is, therefore, important for the investigation of the characteristics of the cool component of symbiotic stars. In particular, we should expect maser emission in the D-type symbiotics for the presence in most of them, as discussed in the previous section, of a Mira-type variability. SiO is also an important cooling agent in the outer atmospheres of oxygen-rich red giants, and is the first step toward the production of circumstellar dust (Muchmore et al., 1987). Therefore, the observation of the molecule in symbiotic objects surrounded by dust envelopes, such as the D-types, is important for the study of the process of dust formation. However, so far the results are far from being satisfying. Extensive search of SiO maser emission was made by Cohen and Ghigo (1980). They were able to positively detect only one object: the symbiotic Mira R Aqr, whose SiO emission was already observed by Lepine et al. (1978) in their survey of cool stars. This star was also observed in the OH and H_2O maser lines, but with negative results (Wilson and Barrett, 1972; Dickinson, 1976). According to Lepine et al. (1978), the SiO emission is probably less affected by the presence of a hot companion, since it is formed in deeper and denser parts of the cool star envelope. This effect was, in fact, already noted in the case of the Mira binaries o Ceti and R Hya (Lepine and Paes de Barros, 1977). More recently, Hollis et al. (1986) observed the 86.24337 Ghz line of SiO from R Aqr with a 2.6 x 3.6" beam width, and found that the SiO emission is unresolved and placed about 1" away from the central star and from the central HII region (see Figure 13-17). For a reasonable assumption on the distance of R Aqr (about 300 pc), Hollis et al. (1986) found that the emisssion is formed too far (about 4.5×10^{15} cm) from the red giant envelope. SiO emission is more probably formed in the circumbinary nebulosity, pumped by the hot star radiation. We also point out the fact that the SiO emission originates in the region opposite to the jet, where no strong radio sources were detected. Probably in this region, the gas is denser and less ionized and/or there is a larger amount of dust and molecules. Mapping of this region in radio and infrared should provide a fundamental basis for understanding the origin of maser emission in circumstellar envelopes and its association with dust and with the nature of the central object.

To conclude this chapter on the radio observations, let us make a more general remark about a major problem: the exact location of the optical counterpart. In fact, the coordinates of the radio source can be derived with very high accuracy (a few milliarcsec), while the astrometric position of the optical counterpart is normally known with much lower precision. It is possible that the radio emission is not coming from the visual star, but from a nearby region (an invisible companion or a small nebula). This is a very important point, since the relative position of the radio and optical sources has strong consequences on the model. Very precise determinations of the astrometric position of these stars are thus urgently needed.

VIII. THE ULTRAVIOLET SPECTRUM OF SYMBIOTIC STARS

VIII.A. INTRODUCTION

The basic problem of the symbiotic phenomenon is to explain the origin of the emission lines and of the strong blue continuum, which should be associated with an ionized region close to the cool star. Can this region be identified with an exceptionally extended transition-region/corona around the cool star, or with a circumstellar nebula ionized by the UV radiation from a hot companion? How can we decide among the different possibilities?

Before the advent of the ultraviolet satellites, several attempts were made to explain the presence of the nebular component in the optical spectrum of symbiotic stars by the presence of a hot star. In particular, Boyarchuk (1966, 1968) made a detailed analysis of the optical energy distribution of symbiotic stars during different activity phases. He was able to identify three spectral components: a stable M giant, a nebular component, and a hot dwarf star, the latter two variable in time. These results clearly anticipate the presence of a strong hot continuum in the UV spectrum of symbiotic stars. But there still was the problem of the unknown amount of the interstellar extinction and the relative faintness of symbiotic stars in the visual.

AG Peg was the first symbiotic star observed in the UV. The Orbiting Astronomical Observatory OAO-2 pointed the star on May 11, 1970, and discovered a strong UV flux with a steep rise to the shortest wavelengths, implying the presence of a luminous hot source, probably a WN6 star with a bolometric luminosity brighter than that of the M3III visible star (Gallagher et al., 1979). The successful launch of the IUE satellite on January 26, 1978 represents an important progress in our knowledge of the nature of the symbiotic phenomenon because of the large amount of new and frequently unexpected results. In particular, the long life-time of this satellite, and its wide and well-balanced use by the astronomical community has been the great advantage of this facility.

In the following, we shall discuss separately the main progresses reached in the fields of the interstellar extinction, continuum energy distribution and emission line spectrum, and of their time variability. We shall also use the expressions "near-UV" and "far-UV" for the 2000-3200 A and 1200-2000 A regions, respectively, which coincide with the long and short wavelength modes of the IUE satellite.

VIII.B. INTERSTELLAR EXTINCTION

Ultraviolet observations have been proved in a number of cases to be the best and even the unique means of determining the interstellar extinction, which is a basic parameter for any model fitting of the observational data. In most symbiotic stars the mid-UV continuum is strong enough to allow the measurement of the interstellar absorption band at 2200 A, which is a prominent feature in the UV extinction curve, and is well correlated with E(B-V). The estimated errors in the corresponding E(B-V) values are around ±0.03/0.05. Figure 11-28 shows some examples of the UV spectra of symbiotic stars showing the 2200 A feature.

For this procedure, the mean galactic extinction curve is generally used. Variations of the interstellar extinction from the mean galactic one are possible, especially for the Large Magellanic Cloud members, and for those objects that are known (or are thought) to be surrounded by dense dust clouds. Different criteria are thus needed for the latter cases and to reduce the estimated errors.

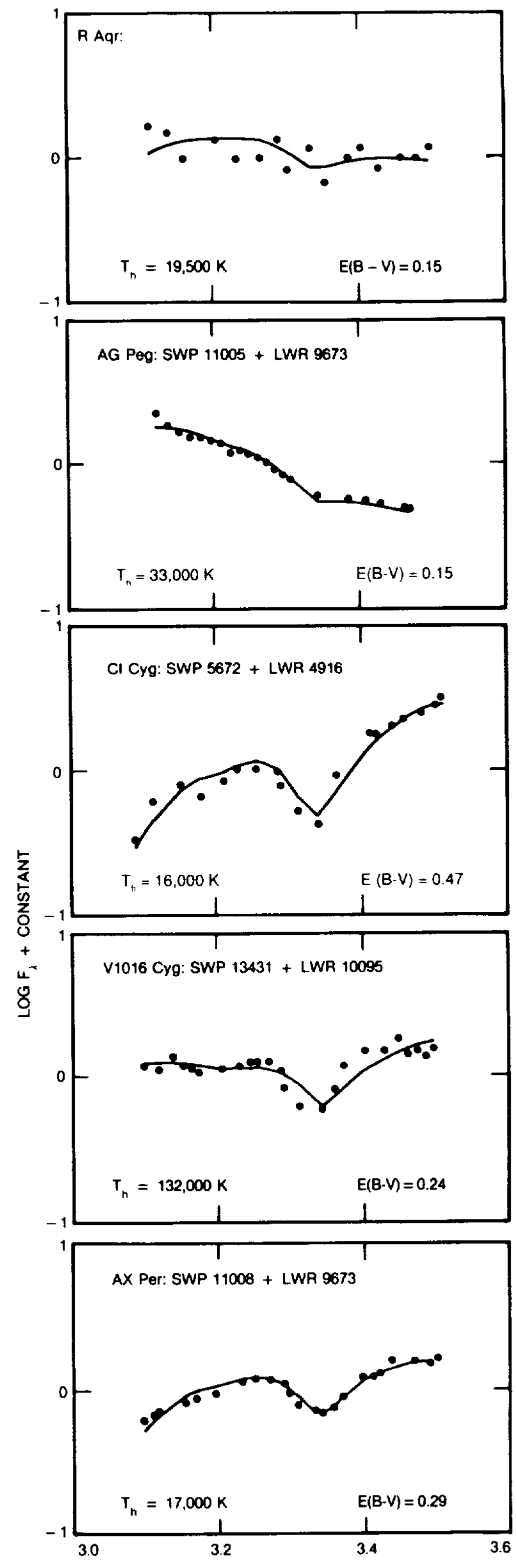


Figure 11-28. Correction for the interstellare extinction in symbiotic stars using the depth of the 2200 A band (Kenyon, 1983a). The hot star fitting temperature T_h and the color excess E(B-V) for a standard extinction curve are indicated.

An independent determination of the i.s. extinction can be derived from the relative intensity of the emission lines in the UV range, or of lines belonging to the UV and optical regions. From the [NeV] and HeII lines in the UV spectrum of V1016 Cyg, Nussbaumer and Schild (1981) obtained E(B-V) =0.3 to be compared with E(B-V)=0.25 as derived from the 2200 A band. For AG Dra, the relative intensity of the HeII lines in the UV provided E(B-V) = ~ 0.05 in agreement with E(B-V) = 0.06 ±0.02 as derived from the i.s. band (Viotti et al. 1983a, 1984a). In this latter star, the far UV continuum is so strong that the region can be observed at high resolution. Several i.s. absorption lines have been identified in spite of the low reddening of this star. The i.s. Lyα line is present as a broad absorption, and from the extension of the wings, a column density of log N(HI) = 20.2±0.2 [N (HI) in cm^{-2}] was derived by Viotti et al. (1983), which again agrees with the above value if one takes into account a lower portion of the i.s. hydrogen in form of H_2 at the high galactic latitude of AG Dra (b = +41°).

In the case of CH Cyg, a prominent Lyα emission line appeared in 1985 (Selvelli and Hack, 1985; Selvelli, 1988; see Figure 11-29a). This line is doubled by a broad absorption due to the

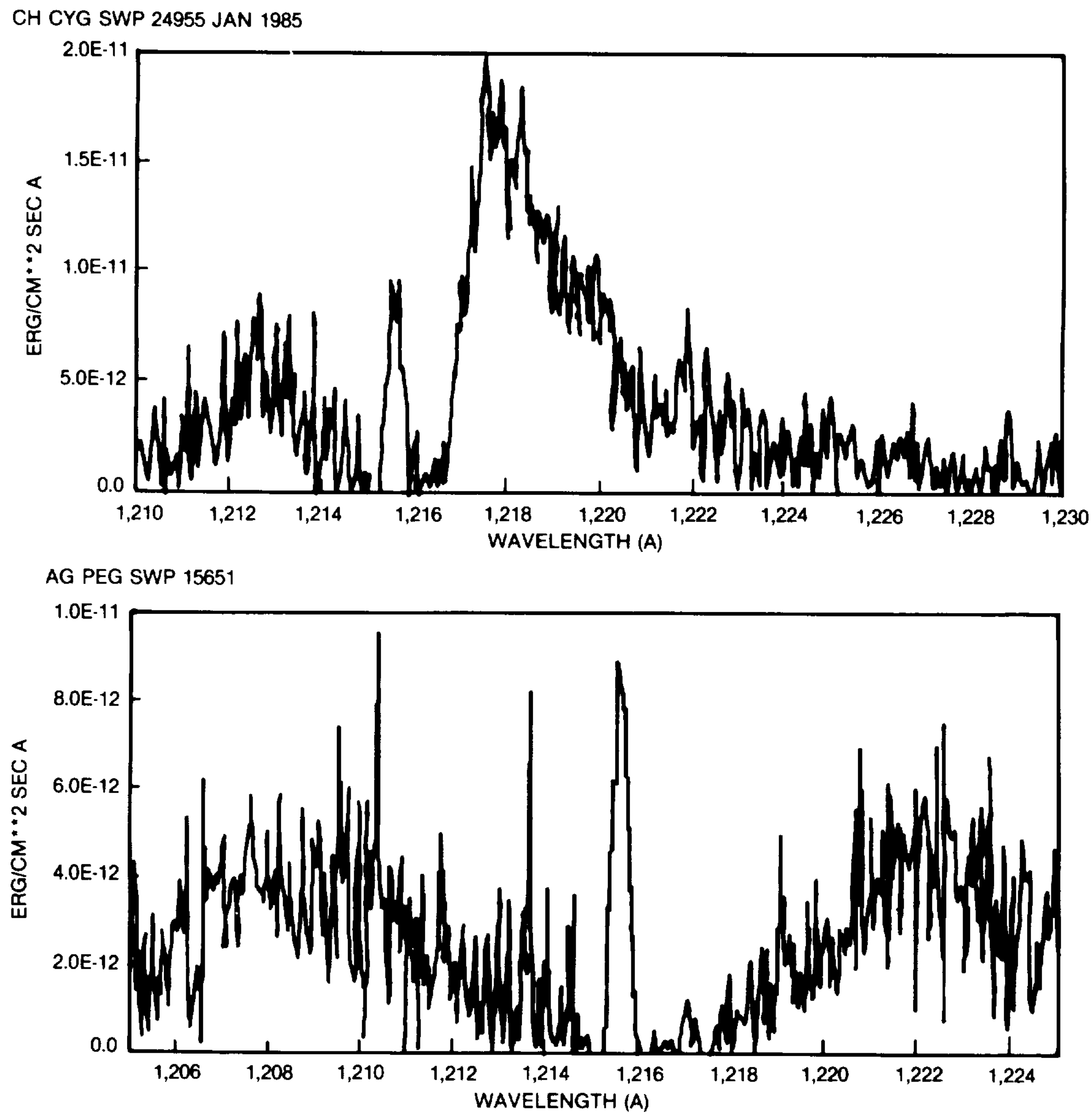


Figure 11-29. Interstellar lines in the high resolution UV spectrum of symbiotic stars. (a) The Lyα region in CH Cyg and AG Peg.

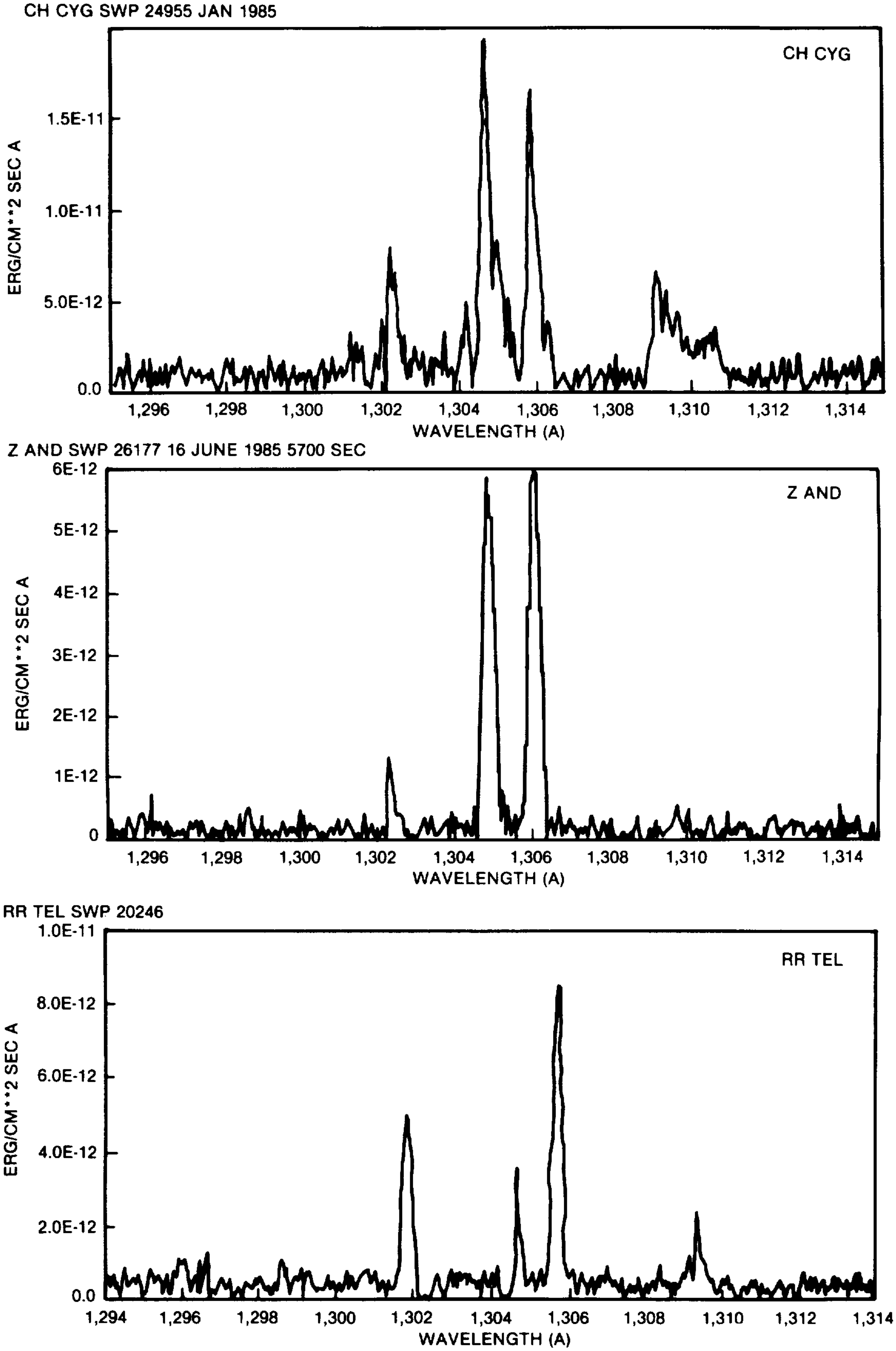


Figure 11-29. (b) the OI triplet in CH Cyg, Z And, and the RR Tel. The position of the interstellar OI and SiII lines is indicated. Note the high negative radial velocity of RR Tel (-61 km s^{-1}).

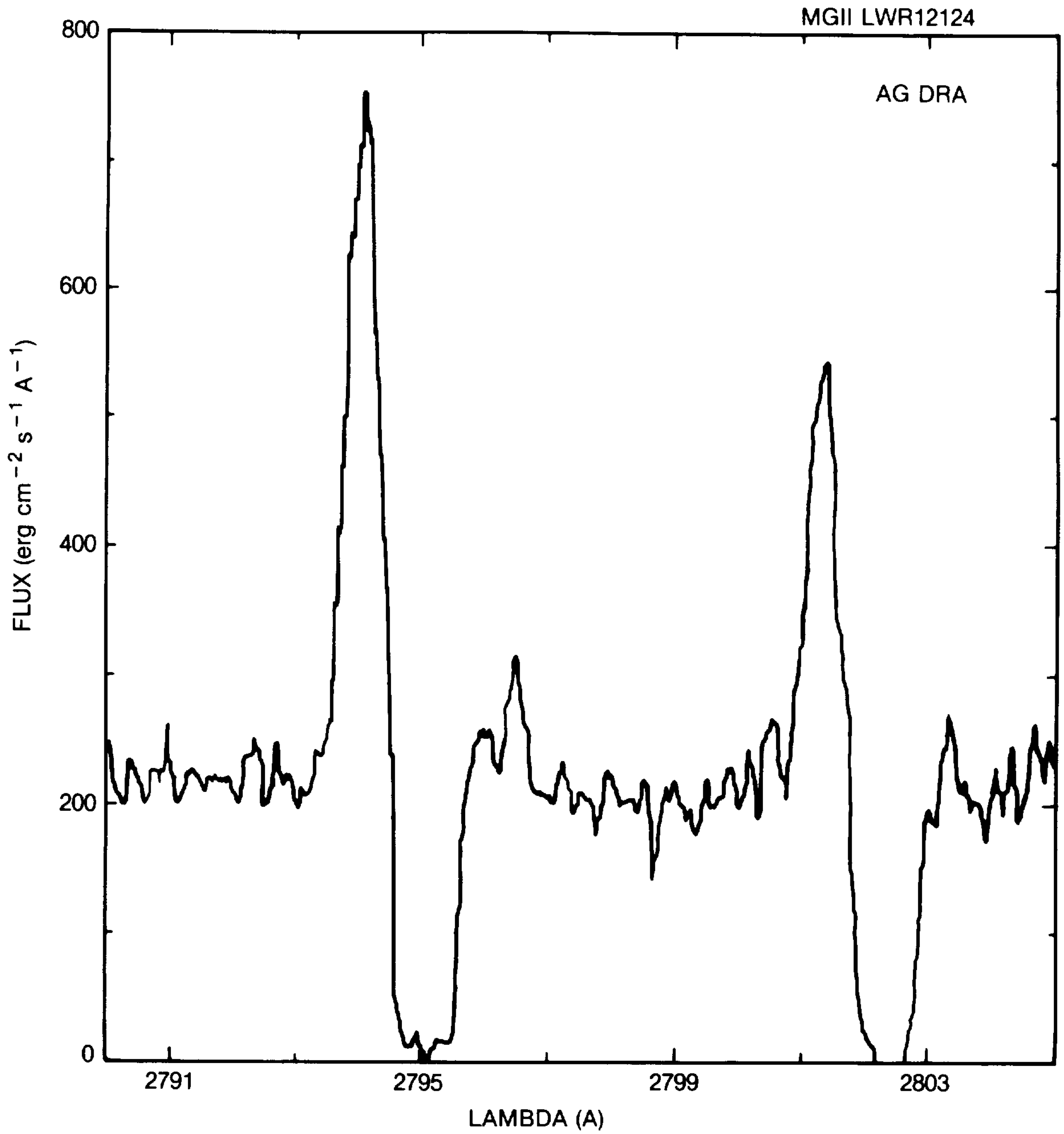


Figure 11-29. (c) The MgII doublet in AG Dra.

interstellar Lyα, whose strength corresponds to logN(HI) = 19.7, or E(B-V) = 0.015 (Viotti, 1988a). Frequently, the interstellar lines fall close to emission lines, and may largely affect its intensity and profile. This may sometimes lead to wrong conclusions. For instance, in Z And, as well as in many other symbiotic stars such as CH Cyg and V1016 Cyg, the OI line near 1302 A is completely absent (see Figure 11-29b), while the other two lines of the resonance triplet are present and strong in emission. The absence of the strongest component of the OI triplet has been frequently interpreted as the result of some rather strange excitation mechanism, or of radiative transfer in the emitting envelope, while the simplest explanation is that the line is missing because of the absorption by the interstellar line (while the other two lines have no i.s. components, being slightly excited transitions). In fact, as soon as the stellar radial velocity is different enough from the i.s. one, the OI 1302 emission line reappears. This is, for instance, the case of the high-velocity stars RR Tel (Figure 11-29b) and AG Dra, whose radial velocities are -61 and -140 km s^{-1}, respectively, so that the i.s. OI 1302 A line falls to the red of the stellar emission line. But it is curious to note that in these stars, the second component of the OI multiplet at 1305 A is much weaker than expected. It is easy to find that in this case, the emission line is coincident in wavelength with the interstellar SiII line at 1304 A. Again, we have an indirect evidence for the presence of an interstellar absorption line, although its true intensity is very hard to be determined with the present spectral resolution of the UV spectra. AG Dra has another interesting feature. In this star, the MgII doublet is characterized by a kind of "inverse P Cygni profile" (Figure 11-29c). Obviously, this is not a real stellar effect, which should be very peculiar for a symbiotic star, but an accidental combination of the blue-shifted stellar emission lines and of the unshifted interstellar components of the same doublet. A similar longward absorption of interstellar origin is seen in the red wing of the CIV 1548 line in the high-velocity (-95 km s^{-1}) symbiotic star EG And (Oliversen et al., 1985). Concerning the resonance doublets, we should finally note that in the case of no wavelength shift between stellar and i.s. lines, the relative strength of the two emission components could be affected by the i.s. absorption, which reduces the stronger component more than the other one, an effect which has been noted for the CIV doublet as discussed below in Section VIII.D.

Table 11-7 summarizes the different determination of the i.s. extinction toward several symbiotic objects derived from UV and optical studies. In general, the UV determinations appear to be in agreement or slightly lower than the optical ones. In some cases, the agreement is poor, being the optical E(B-V) much larger. In these cases, we preferred the UV determinations. It should be finally observed that most of the symbiotic stars are little reddened, which makes these objects good targets for future space observations beyond Lyα in the far-UV, as also discussed below.

VIII.C. THE ULTRAVIOLET CONTINUUM

Figure 11.30 shows the low resolution IUE spector of some symbiotic stars. The majority of them display a smooth continuum which is rather flat in the near-UV, but with a clear far-UV excess. Once the fluxes are corrected for the i.s. extinction, the continuum gradient in the far-UV becomes quite steep and frequently approaches the Rayleigh-Jeans tail of a black body radiation, which corresponds to black body temperatures $\geqslant$ 40,000 K. This implies that the size of the "hot source" could be as small as one-tenth of a solar radius or even less, close to the size of a hot subdwarf. In addition, most of its energy is radiated outside the IUE range shortwards the Lyman continuum. It is then difficult to have a precise estimate of the bolometric luminosity of the hot source, unless we use other methods. In fact, as for the central stars of the planetary nebulae, we can derive the Zanstra temperature from the emission line fluxes. For instance, the intensity of the HeII line at 1640 A provides a measure of the photon flux shortwards of the helium ionization limit at 228 A. For more details on the method, the reader should refer to the many publications on the matter (e.g., Osterbrock, 1974; Pottasch, 1984) and to the papers on individual symbiotic stars. One not negligible problem is the true energy distribution of the far-UV spectrum of the hot source, which is fairly different from that of a black-body. The hot source itself could be not a star but the innermost layers of an accretion disk, or even a "hot spot" somewhere in the environment of the symbiotic object, or on the cool star surface. It is difficult at this stage to distinguish among all these possibilities, although, as we shall show later, energy balance considerations and, especially, the time variability may help to solve this problem.

If the far-UV continuum is produced by the photosphere of a hot dwarf star, we should expect to see some photospheric absorption lines. The typical features that could be seen at low resolution for effective temperatures of 40,000 K or more, are the resonance doublets of NV, CIV, and SiIV, and the excited lines of HeII 1640 A, NIV 1718 A, and OV 1371 A. The resonance lines and the HeII line are always coincident with prominent emission lines of the symbiotic spectrum, and any contribution from a photospheric absorption is thus masked. The subordinate lines of NIV and OV are generally not seen (or present as weak emissions). The most promising feature associ-

TABLE 11-7. INTERSTELLAR EXTINCTION TOWARD SYMBIOTIC STARS

Object	E(B-V) (mag)	LogN(H) (a) (cm^{-2})	Method (b) (Reference)
Z And	0.35	==	2200 (1)
EG And	0.07	==	UVc (2)
CH Cyg	0.015	19.7	Lyα (3)
CI Cyg	0.40	==	2200 (4)
V1016 Cyg	0.28	==	2200, UV1(5), opt (6)
V1329 Cyg	0.37	==	2200, opt+UV1 (7)
AG Dra	0.06±.02	20.2	Lyα, 2200, UV1 (8)
YY Her	0.18	==	2200 (2)
V443 Her	0.31±.04	==	UVc (2)
BX Mon	0.20±.05	==	opt (9)
SY Mus	0.40	==	2200 (10)
AR Pav	0.30	==	2200 (8,11), radio (12)
AX Per	0.29	==	2200 (2)
AG Peg	0.12±.03	==	2200 (2,13), radio (12)
RX Pup	0.3-1.0	==	opt (14), 2200 (8,15)
HM Sge	0.6	==	2200 (2,16), opt (17)
RR Tel	0.10±.03	==	2200,UVI (18)
PU Vul	0.49	==	UVc (19)
R Aqr	<0.10	<20.2	Xray,opt (20), 2200 (2)
RS Oph	0.73±.10	21.0	UV (21), Xray (22)

Notes to the table: (a) Neutral hydrogen column density from radio or X-ray observations. (b) 2200: depth of the 2200 A interstellar band; Lyα: extension of the i.s. Lyα absorption; UVc: UV energy distribution; UV1: flux ratio of UV emission lines; opt: flux ratio of optical emission lines; Xray: X-ray spectrum; radio: radio maps.

References: (1) Viotti et al., 1982. (2) Kenyon, 1983a. (3) Viotti, 1988a. (4) Baratta et al., 1982. (5) Nussbaumer and Schild, 1981. (6) Ahern, 1978. (7) Muller et al., 1986. (7) Viotti et al., 1983; Viotti et al., 1984a (8) Kenyon and Webbink, 1984. (9) Viotti et al., 1986. (10) Michalitsianos and Kafatos, 1984. (11) Slovak, 1982b. (12) Burnstein and Heiles, 1982. (13) Penston and Allen, 1985. (14) Klutz et al., 1979. (15) Kafatos et al., 1982; Kafatos et al., 1985. (16) Mueller and Nussbaumer, 1985. (17) Willson et al., 1984. (18) Penston et al., 1983. (19) Friedjung et al., 1984. (20) Viotti et al., 1987. (21) Snijders, 1987. (22) Mason et al., 1987.

ated with a hot photosphere could be the FeIV-FeV blend near 1400 A, which is seen in many hot subdwarfs (e.g., Bruhweiler et al., 1981; Rossi et al., 1984). These absorptions have also been identified in the UV spectrum of WR stars (Fitzpatrick, 1982). So far, there is no indication of this blend in the UV spectrum of symbiotic stars, but certainly a careful analysis of high S/N spectrograms should give a more precise answer on this regard. We should also consider that the hot component of a symbiotic system might be subject to an intense high-velocity wind producing strong and wide P Cygni profiles in the resonance and subordinate lines, which should easily be seen also at low resolution. But, as discussed below, P Cygni profiles are rather rare among symbiotic stars.

The continuum of symbiotic stars is generally too weak to be observed at high resolution with IUE, with two important exceptions: AG Dra and CH Cyg. AG Dra has a very intense UV continuum that can be detected at high resolution in less than one hour. The continuum appears featureless, apart from the many interstellar lines discussed in the previous section, and the narrow P Cygni absorption of the NV 1240 A doublet. In particular, there is no trace of the FeIV-FeV, which, as discussed above, should be present in

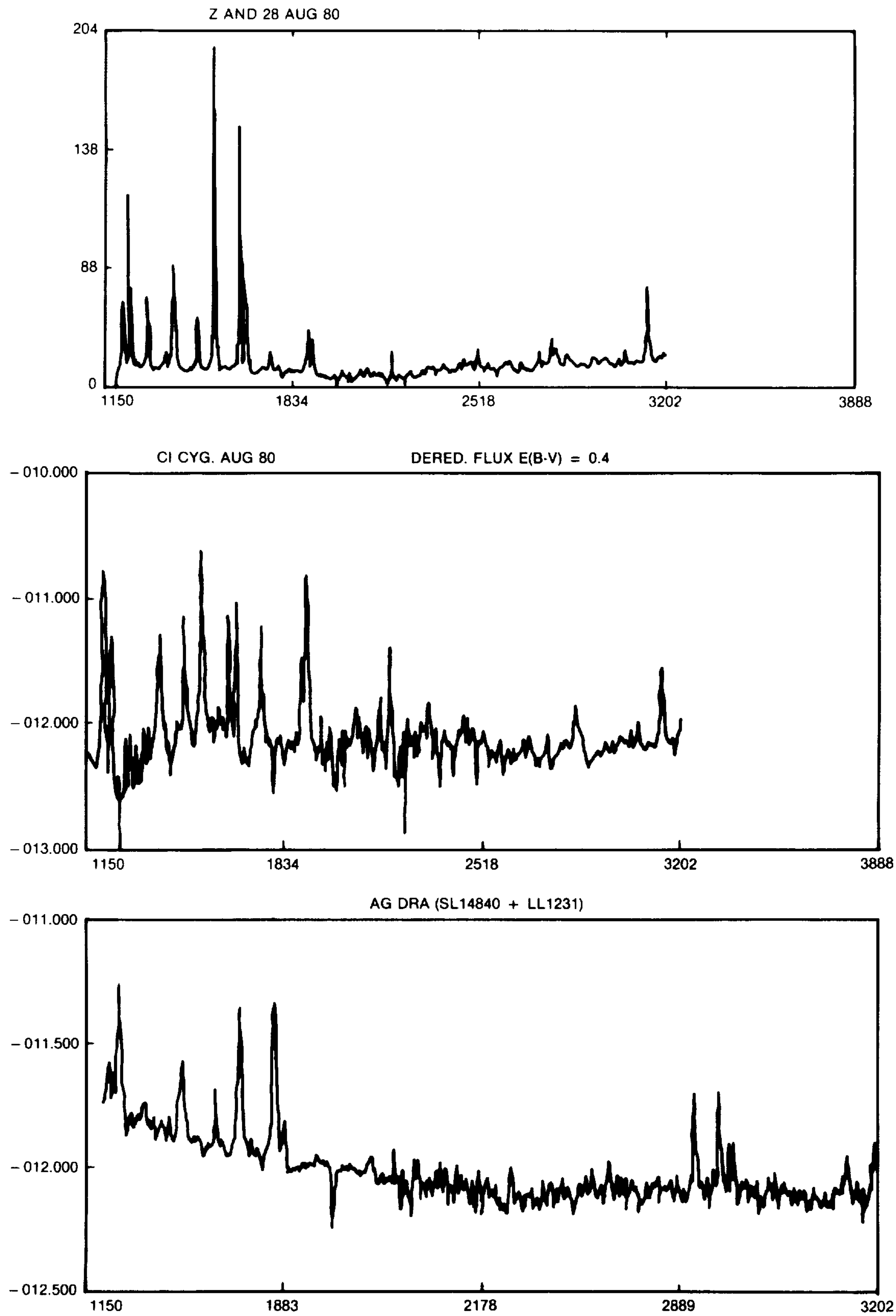


Figure 11-30. The low-resolution ultraviolet spectrum of symbiotic stars observed with the IUE satellite.

the photospheric spectrum of a star with a temperature similar to that of the UV continuum of AG Dra. More complex is the case of CH Cyg, which displays (during the light maximum) a rich absorption line spectrum. The lines—mostly of FeII, NiII, and of other singly ionized metals—appear rather narrow and slightly violet-shifted, which should be an indication of lines formed in a diluted medium, rather than in a stellar photosphere. The large spectral variability of this star is also suggestive of a nonphotospheric origin of the observed features.

To summarize, so far, there is no direct evidence for photospheric features in the far-UV continuum of symbiotic stars, that could support the hot subdwarf hypothesis. But again, these could have been masked by the rich emission line spectrum. Or, more simply, the "photospheric spectrum" actually is a kind of "mild" P Cygni-type spectrum like the central stars of planetary nebulae, but with a lower expansion velocity of the atmosphere.

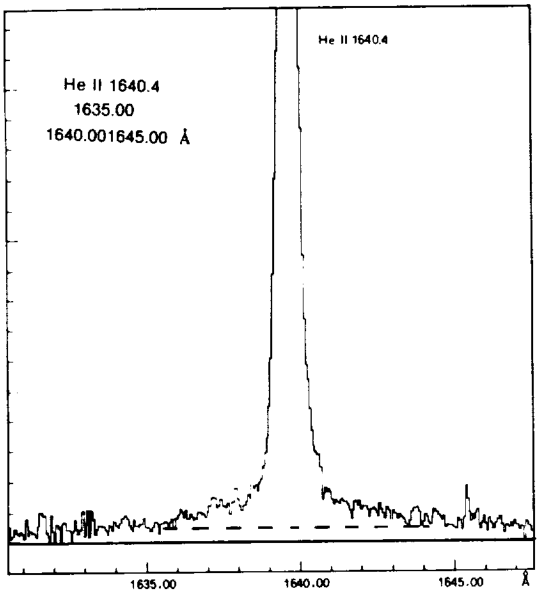
The near-UV continuum generally appears flat and featureless and could be considered as a continuation of the Balmer continuum. Thus, it is probably produced in an optically thin or thick "nebular" region, i.e., in the ionized parts of the circumstellar gaseous envelope. Several attempts have been made to fit the UV continuum of symbiotic stars with a two-component model (e.g., Slovak, 1982; Penston et al., 1983; Kenyon and Webbink, 1984; Cassatella et al., 1988b; Fernandez-Castro et al., 1988). In general, the derived parameters largely depend on the assumed values for the hot star temperatures, so that there is a large uncertainty on the physical structure of the system. In particular, in the majority of cases, it appeared hard to discriminate among the two most favored models: hot star or accretion disk. In other words, we have so far no *direct* proofs of the presence of a hot stellar component (i.e., a hot star) in a symbiotic system, nor, as we shall discuss later, of an accretion disk surrounding a dwarf star.

VIII.D. THE EMISSION LINE SPECTRUM

As in the optical region, the UV spectrum of symbiotic stars in characterized by a great number of emission lines belonging to a wide range of ionization energies. In most objects, very prominent are the resonance lines of NV, CIV, SiII, SiIV, AlII, AlIII, and MgII, and the intercombination lines of CII, CIII, OI (λ 1641), OIII, SiIII, NIII, and NIV. HeII is present with the strong line at 1640 A, and with the weaker Pickering series, in the near-UV range. The highest ionization energy species are represented by OV, NV,[MgV], and [CaVI] (e.g., Penston et al., 1983). But FeII is also frequently observed in the UV spectra of symbiotic stars. A very rich FeII spectrum is displayed by RR Tel (Penston et al., 1983) and by CH Cyg after the outburst (Marsi and Selvelli, 1987). It may be noted that the emission lines are frequently so intense as to be easily detected with IUE at high resolution with very short exposure times. We may thus have an accurate measure of the flux ratios and of the line profiles. Line profiles may, in fact, provide a means to derive the velocity fields in the stellar environments. P Cygni profiles are difficult to see because of the weakness of the continuum, which, in general, cannot be observed with IUE at high resolution. The presence of a shortward displaced absorption can be indirectly inferred by the asymmetry of the emission line profile, or from the doublet intensity ratios, as discussed in Chapter 13. In the case of AG Dra, a P Cygni profile is clearly visible in the NV doublet, with an absorption component shifted by -120 km s^{-1} and extending to -170 km s^{-1} (Viotti et al. 1983, 1984; Figure 11-31a). This component is not seen in the lower energy CIV and SiIV doublets and might suggest a very high temperature (>1-2x10^5K) for the expanding envelope (however, see later the discussion of models).

As can be seen in Table 11-8, frequently the flux ratio of the components of the resonance doublets of NV, CIV, SiIV, and MgII largely deviates from the optically thin value of two. The anomalous resonance doublet ratio in symbiotic stars (and related objects) was noted and discussed among others by Nussbaumer and Schild (1981), Feibelman (1983), Kafatos et al. (1985), and especially Michalitsianos et al. (1988).

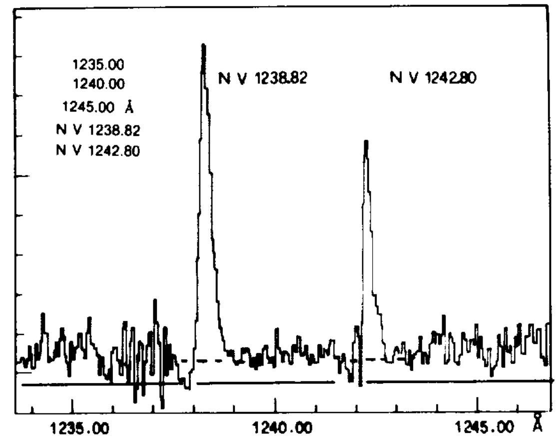
The HeII 1640 A line is the strongest emission in the UV spectrum in many symbiotic stars. In



AG Dra, the line appears as a narrow peak, with a FWHM of 0.50 A, and very broad emission wings with a FWHM of about 6 A (Viotti et al., 1983; Figure 11-31a). Broad wings have also been observed for the strongest emission lines (CIV, HeII, NV, and CIII) in RR Tel (Ponz et al., 1982 Figure 11-31b), V1016 Cyg (Kindl et al., 1982), and in the outburst spectrum of Z And (Cassatella et al., 1988a). These broad features could be produced by Thomson scattering in the emitting region. Alternatively, if Doppler broadened, the wings should indicate the presence of a high-velocity (rotational or expansion velocity) region, which could be identified with the accretion disk or with matter streaming in the system. Note that in the accretion disk hypothesis, the wings of the higher temperature lines should be broader.

In RR Tel Penston et al. (1983) found a systematic increase of the line width of the narrow emission lines with ionization potential from 40 to 86 km s^{-1}. A similar behavior is present in AG Dra (Viotti et al., 1983) and HM Sge (Mueller and Nussbaumer, 1985). This result again, if confirmed, should be an important element to understand where emission lines are formed.

A rather extreme case is represented by AG Peg, whose UV spectrum shows quite a variety of line profiles (see Figure 11-31c) that are also variable in time. As discussed by Keyes and Plavec (1980) and by Penston and Allen (1985),



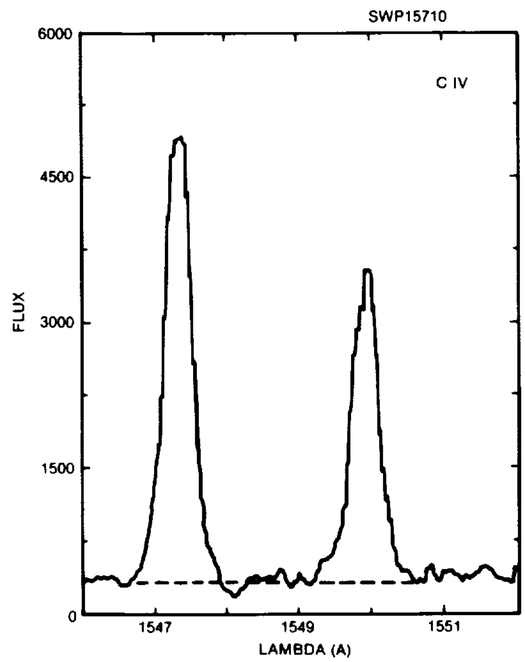


Figure 11-31. The UV emission line profiles in symbiotic stars. (a) NV, CIV, and HeII in AG Dra. (b) NV, CIV, and HeII in RR Tel with broad wings. HeII is flanked by the narrow OI forbidden line. (c) NV, NIV], CIV, and HeII in AG Peg. The central absorption in NIV] is a processing artifact.

in 1979, the HeII 1640 line appeared very broad with a triangular shape and a FWHM of 4 A. The CIV line was represented by a narrow peak, while the 1551 component displayed a broad red wing. Later, in January 1985, the CIV doublet was characterized by two asymmetric peaks of about equal intensity, low velocity P Cygni absorption components, and broad wings (Figure 11-31c). It should finally be remarked that in this star also the intercombination line of NIV at 1486 A presents a broad wing below the strong emission peak.

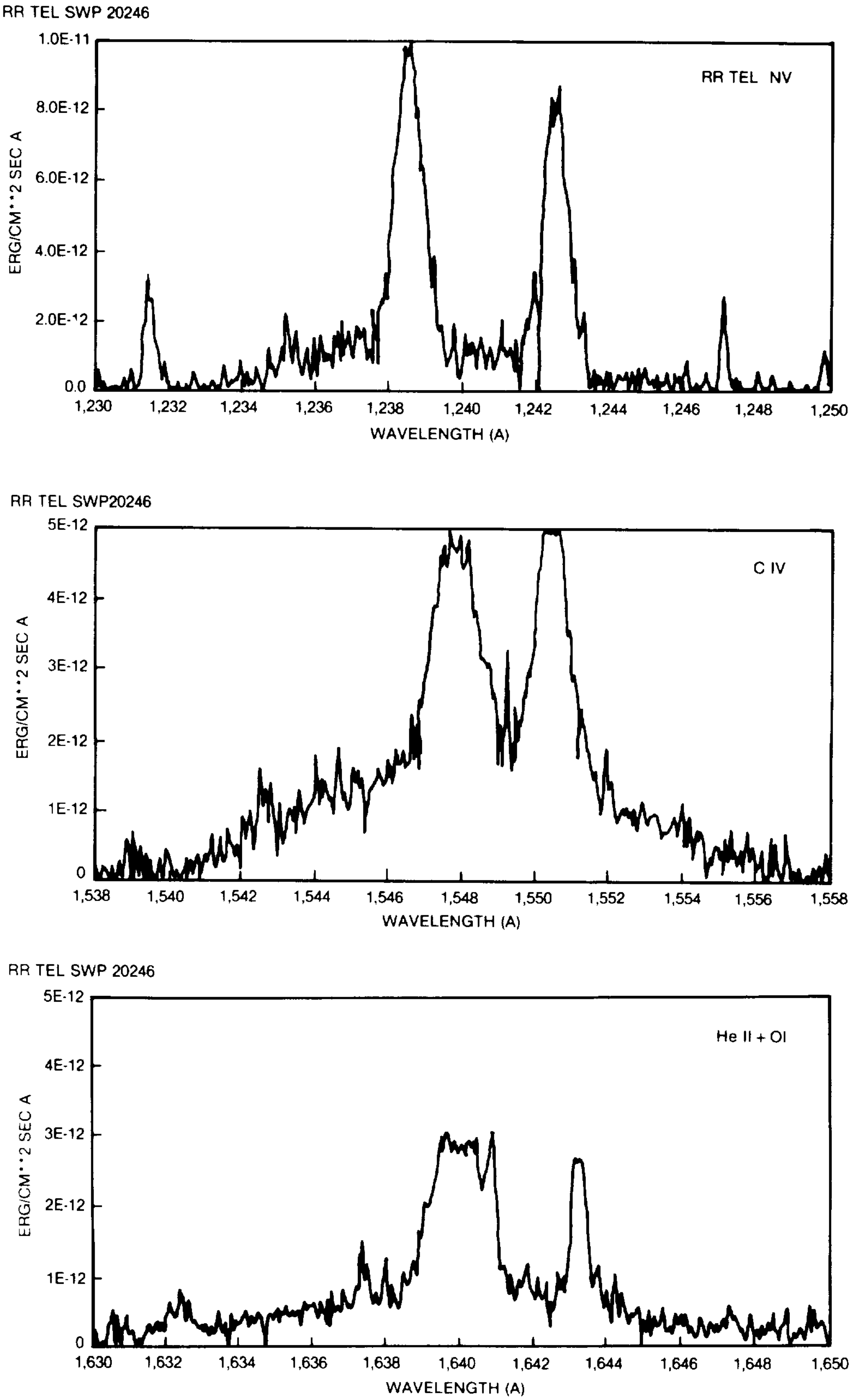


Figure 11-31. (b)

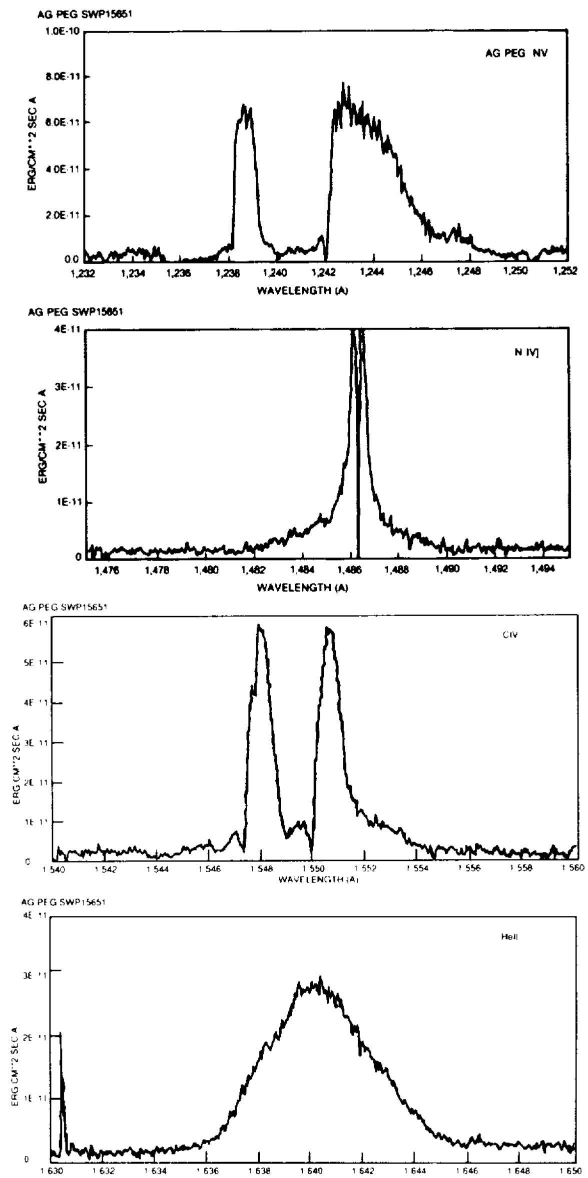


Figure 11-31. (c)

VIII.E. UV VARIABILITY

The very long lifetime of the IUE satellite has so far represented a unique occasion to collect the UV spectra of many symbiotic stars on a time scale of one decade. It was thus possible to follow spectral changes possibly associated with the long-term symbiotic activity, and with any orbital motion. Since the start of full operation of IUE (April 1978) a number of "outbursts" occurred in the following symbiotic stars: PU Vul (1978; first observed in 1979), AG Dra (three outbursts in 1980, 1985, and 1986), Z And (two outbursts in 1984 and 1985), CH Cyg (the 1984 "radio outburst"), and AX Per (1988). These outbursts were followed by a variety of spectral evolution without a clear common trend. For instance, the 1984 outburst of Z And, which was of small amplitude with respect to its light history, was characterized by a slight decrease of the UV emission line and continuum temperature (Viotti et al., 1984b; Cassatella et al., 1988a). The visual fading of CH Cyg after the radio brightening was followed by a fading of the UV continuum and a large increase of the line excitation with the appearance of high temperature lines and a rich FeII emission line

TABLE 11-8. EMISSION LINE INTENSITIES IN THE ULTRAVIOLET SPECTRUM OF SYMBIOTIC STARS

		Emission Line Fluxes[2]					
Wavel.[1]	ion	Z And (3)	CH Cyg (4)	V1016 Cyg (5)	AG Dra (6)	RR Tel (7)	AG Peg (8)
1215.67	Lyα	=	2160.:	=	=	=	=
1238.80	NV	88.4	15.0	170	26.4pc	p	3500n
1242.78	NV	47.6	17.8	100	>13.5pc	p	bl
1371.29	OV	=	=	=	3.0n	80n	420n
1393.73	SiIV	20.9	35.4	49	3.2	260	312n
1402.73	SiIV	12.4	85.7	42	2.6	172	195n
1401.16	OIV]	24.9	=	94	8.1	442	36
1404.81	OIV]	9.4	=	50	3.3	233	34
1486.50	NIV	>29.9s	5.0	140	6.5	514	2250n
1548.20	CIV	>177.0s	57.9	650	29.2	384	6780n
1550.77	CIV	115.0	101.3	460	16.8	210	bl
1640.43	HeII	212.0	47.5	510	160.0nw	1880nw	5800n
1641.3	OI]	7.4	35.0	17	=	92	=
1666.15	OIII]	28.0	43.4	100	3.1	427	880
1718.52	NIV	=	=	4.2	=	13.6	1070n
1749.67	NIII]	9.6	8.0	43	0.4	93	190
1753.99	NIII]	3.1	=	7.5	0.2	26.3	=
1785.26	FeII	=	145.7	=	=	5.5	p
1892.03	SiIII]	22.4	25.7	100	1.4	280	350
1906.68	CIII]	=	2.1	<=10	=	11.1	=
1908.73	CIII]	33.5	138.8	500	0.6	1130	500
2325.40	CII]	p	41.9	58	=	52.8	=
2326.93	CII]	=	19.0	=	=	18.5	=
2506.43	FeII	=	97.4	=	=	26.8	=
2508.34	FeII	=	88.1	=	=	40.6	=
2733.30	HeII	7.8	=	27	4.1	70.8	330
2782.7	MgV]	=	=	88	=	446	=
2795.52	MgII	p	s	82	3.8	488	p
2802.70	MgII	p	s	79	3.1	320	p
2926.58	FeII	2.7	149.3	3.0	=	8.5	p
3132.86	OIII	40.2	=	240	...	473	13
3203.04	HeII	p	=	66	11.7	p	530n

Notes to the table: (1) Wavelengths in A (in vacuum below 2000 A). (2) Fluxes in 10^{-13} erg cm^{-2} s^{-1}, not corrected for the reddening. Other symbols: p: present; s: strong and saturated; bl: blended; n: broad line (FWHM>0.3A); w: broad wings (FWHM = 2 - 6 A); pc: P Cygni profile. (3) Altamore et al., 1981. (4) Selvelli and Hack, 1985; Marsi and Selvelli, 1987. (5) Nussbaumer and Schild, 1981. (6) Viotti et al., 1983. (7) Penston et al., 1983. (8) Penston and Allen, 1985; line fluxes include both broad and narrow components.

spectrum (Selvelli and Hack, 1985). The large brightening of AG Dra of November 1980 was associated in the UV with a large increase of the UV line and continuum flux, but the line excitation remained the same as at minimum, as indicated by the nearly constant NV/CIV resonance doublet ratio (Viotti et al., 1984a). Also, the P Cygni profile of NV discussed in the previous section remained nearly unchanged before, during, and after the light maximum. The rising phase of the symbiotic nova PU Vul was not observed with IUE, but the deep fading of 1980 and the subsequent recovery did not display a significant change of the near-UV spectrum, which is dominated by the A-type component (Friedjung et al., 1984). It is obvious to conclude from the above examples that different mechanisms should be responsible for the observed phenomena and that each event should be treated individually. It is also evident that UV observations alone cannot provide an unambiguous model of the outburst and that multifrequency observations are always needed for an effective discrimination among possible mechanisms.

Spectral variations in the ultraviolet were occasionally observed by several authors also when the star was in a quiescent phase. In some cases, when the star was monitored by IUE for a long enough time, periodic or quasi-periodic variations of the continuum and emission line intensity were clearly identified. For instance, Viotti et al. (1984a) found that AG Dra, during the period before the main 1980 outburst, underwent a large change of the UV spectrum in phase with the U-band periodic variations discovered by Meinunger (1979). For V1329 Cyg, Nussbaumer et al. (1986) found a periodic ("modulation") of both the flux and wavelength position of the emission lines. The derived period of 964 days is in agreement with the optical light curve. In the case of RR Tel, Hayes and Nussbaumer (1986) found a gradual decrease of the UV line fluxes during the period 1978-1984, without evidence of periodicity. The best example is probably represented by the prototype Z And. The star was observed many times with IUE during the long quiescent period preceding the minor 1984 outburst. From a study of the UV spectrum of Z And during 1978-1982 Fernandez-Castro et al. (1984) found large amplitude periodic changes of the intensity of the ultraviolet emission lines and of the Balmer and far-UV continuum. These variations appeared in phase with the optical photometry (Taranova and Yudin, 1981; Belyakina, 1985) and suggested a period of about two years. A different case is that of the eclipsing binary CI Cyg, which was monitored by IUE during its 1980 and 1982 eclipses. The star, however, was at minimum activity, so that the variations during eclipse were of small amplitude in all the wavelength ranges. Stencel et al. (1982) found that during the 1980 eclipse, the HeII 1640 emission line largely faded, while NV, which should be formed in the same region, did not change. A decrease of the UV continuum by about a factor 2.5 was noted by Baratta et al. (1982).

From a high dispersion study of the D-type symbiotic RX Pup, Kafatos et al. (1985) discovered a large variability of the emission line profiles. HeII 1640 and NIV] 1486 appeared sometimes double, while the CIV resonance lines were characterized by a variable 1548/1550 doublet flux ratio, frequently below the optically thick value of unity (Figure 11-32). This peculiarity is a mean to investigate the structure and temporal behavior of winds in symbiotic stars and similar objects, as discussed by Michalitsianos et al. (1988). Long-term variation of the emission line fluxes was also found by Kafatos et al. (1986) in the "jet" of R Aqr. They also observed that the variations were not correlated with the Mira light curve of R Aqr, and the time scale of about one year and a half was larger than the Mira period.

More details about the UV spectral variations will be given in Chapter 13 devoted to the description of individual objects.

VIII.F. FAR-UV OBSERVATIONS

As discussed above, many symbiotic stars display in the SWP range of IUE a strong continuum that should extend far beyond the IUE short wavelength limit. The presence of prominent high-ionization emission lines also requires high-energy photons from a very hot continuum. Therefore, it is expected that symbiotic stars should be strong EUV sources, also because of the small interstellar extinction found in many of them. Several symbiotic stars were, in fact, pointed by the Voyager 1 and 2 experiments (Holdberg and Polidan, 1987). These spacecrafts are well known for their exploration of the outer solar system objects. Each Voyager brings a low-resolution spectrometer that is sensitive in the range 500 to 1700 A, with an effective resolution of 25 A (Broadfoot et al., 1981), a region that

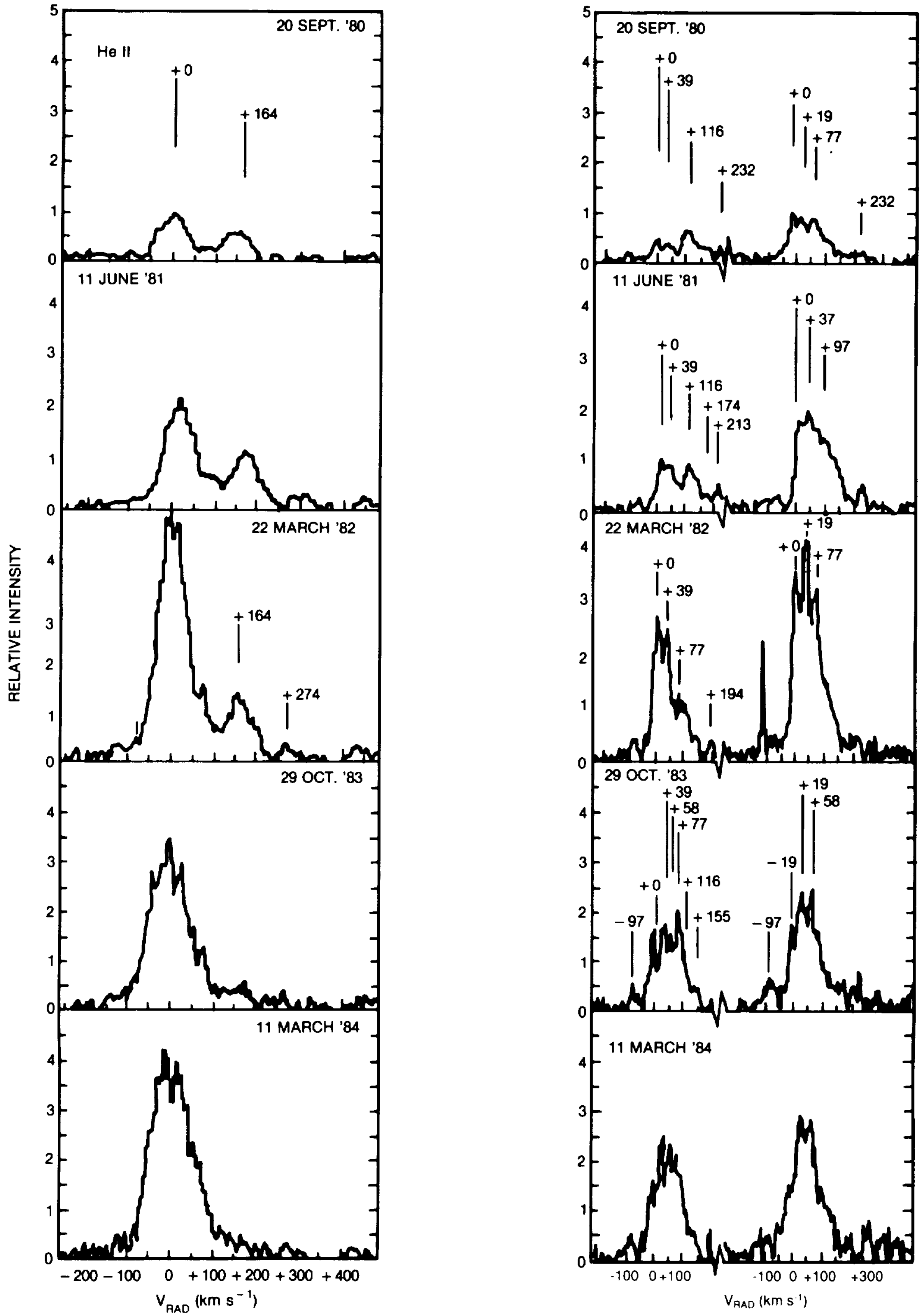


Figure 11-32. Time variability of the HeII and CIV profiles in RX Pup (Kafatos et al. 1985).

includes the Lyman continuum and several important transitions such as the Lyman series and the OVI 1032 A line. Although the Voyager spectra have not yet been published at the time of writing this report, we have been informed that, in spite of the rather low sensitivity of the instruments (flux limit of about 10^{-12} erg cm^{-2} s^{-1} A^{-1}), the observations were quite successful. The analysis that is in progress will provide important information about the high-ionization emitting regions and the temperature of the hot continuum.

IX. X-RAY OBSERVATIONS OF SYMBIOTIC STARS

IX.A. INTRODUCTION

The spectrum of symbiotic stars is dominated by a large number of prominent emission lines belonging to species with very high ionization energies up to more than 100 eV. Forbidden and intercombination lines of MgV, OV, and CaVI have been identified, for instance, in the well-studied object RR Tel (Penston et al., 1983), while [FeVII] and the unidentified emission at 6830 A, generally attributed to a highly ionized ion (Allen, 1980), are present in the optical region (Thackeray, 1977). This fact may suggest the existence of efficient ionization processes somewhere around the symbiotics that could be associated with high temperature plasmas. Therefore, we expect that some symbiotics, namely those displaying emission lines with the highest ionization stages and, which are, obviously, not too faint and not too reddened, should be X-ray sources. There are other "model-dependent" arguments. For instance, X-rays could be produced by the tail of the very hot and luminous UV continuum found in many symbiotic stars, such as AG Dra. In a binary system, accretion processes may lead to the formation of a hot disk and boundary layer around the dwarf component. Accretion onto the surface of a degenerate star could produce thermonuclear burning of the hydrogen-rich accreted shell. At any event, we should expect a strong dependence of the X-ray flux on the symbiotic activity.

The X-ray astronomy has largely profited from the extensive survey with the HEAO-2 satellite (the Einstein Observatory), which has greatly increased the number of different categories of stellar X-ray sources. Several symbiotics have been pointed at with HEAO-2, but only in a few cases, that is, 5 out of about 20, X-ray emission was detected. The positive detection includes 3 D-type, nova-like symbiotics: V1016 Cyg, HM Sge, and RR Tel (Allen, 1981), the S-type AG Dra (Anderson et al., 1981), and one related object GX 1+4 = 4U 1728-24 (Davidsen et al., 1977). All but one (GX 1+4) are soft X-ray sources. One star, HM Sge, was observed three times (Willson et al., 1984). HEAO-2 also provided the upper limits to the X-ray flux for about 15-20 more objects (Allen, 1981; Wallerstein, quoted in Willson et al., 1984; Seward, 1985) including CH Cyg, which will be discussed below. In the case of the symbiotic Mira R Aqr and of Mira itself, Jura and Helfand (1984) claimed a marginal but positive detection, while a reanalysis of the HEAO-2 data led to the conclusion that one can only put an upper limit (Seward, 1985; Viotti et al., 1986b, 1987).

New observations were carried out during 1984-86 with the EXOSAT satellite, and two new positive detections were added: R Aqr (Viotti et al., 1985) and CH Cyg (Leahy and Taylor, 1987). In addition, the strong source in AG Dra was monitored during three different phases of its recent activity. Figure 11-33 shows the EXOSAT map of R Aqr in June 1985. We shall discuss in the following the results of these observations. Table 11-9 summarizes the main X-ray observations of symbiotic stars based on HEAO-2 and EXOSAT observations.

IX.B. THE SYMBIOTIC NOVAE

The three symbiotic novae—RR Tel, V1016 Cyg, and HM Sge—were first observed in X-rays in 1979 with the Image Photon Counter (IPC) onboard of HEAO-2 (Allen, 1981). The detected fluxes are weak, but Allen noted that in the more recently exploded objects V1016 Cyg and HM Sge, the flux was larger than in the older symbiotic nova RR Tel. This may suggest a secular decrease of the X-ray luminosity after the outburst, with an e-folding time of about 7 years.

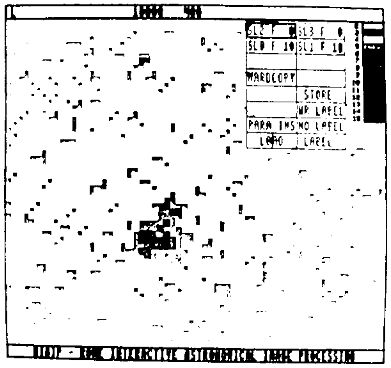


Figure 11-33. X-ray observations of the Mira-type symbiotic R Aqr with the EXOSAT satellite (Low-Energy LE1 detector, Thin Lexan filter) in June 1985.

Willson et al. (1984) have reanalysed the data on HM Sge and RR Tel and added a new observation of HM Sge obtained in 1981. They noted a decrease of the X-ray flux of the latter star. The change of the luminosity of HM Sge and the comparison of the data for the three stars are again consistent with a similar X-ray luminosity at the outburst followed by a decline with a decay time in the range from 5 to 50 years. Kwok and Leahy (1984) have further analyzed the HEAO-2 1979 data of the symbiotic novae and concluded that the observed spectra can be fitted with a thermal bremsstrahlung from circumstellar gas at about 0.4 to 1.5 keV. They propose that the hot region is shocked gas, resulting from the collision of the winds from the hot and cool star of a binary. After the outburst, the shocked region expands and produces the observed gradual decrease of the X-ray luminosity.

Although three different papers come to the same conclusion, one should pay attention to the

TABLE 11-9. X-RAY OBSERVATIONS OF SYMBIOTIC STARS

Object	Instr. (a)	Date	Phase (b)	X-ray Source Range (c)	Flux (d)	N(H) (e)	Flux (f)	Ref.
RR Tel	HEAO	79/4/9	decl	.1-3.	3.	2.	3-4	1
....	....	......	...	.2-4.	4.8	2.2	6.7	2
....	EXO	84/5/4	...	.02-1.	<14.	==	==	3
V1016Cyg	HEAO	79/11/24	max	.2-4.	4.3	4.6	8.2	2
HM Sge	HEAO	79/4/9	max	.2-4.	36.	6.2	50.	2
....	....	......	...	.1-3.	28.	17.	480.	1
....	....	81/4/8	...	...	17.	23.	36.	1
AG Dra	HEAO	80/4/11	min	.2-1.	21.	23.	36.	4
....	EXO	85/3/15	out	.02-2.5		weak		5
....	EXO	85/6/5	min	...		strong		5
....	EXO	85/11/5	min	...		strong		5
....	EXO	86/2/14	out	...		no detect		5
R Aqu	HEAO	80/6/21	min	.2-3.5	<3.	==	==	6,7
....	EXO	85/6/14	max	.2-1.		1.5	200.	7
....	EXO	85/12/24	min	...		1.5	200.	7
CH Cyg	HEAO	79/10/ 29	max	.2-4.	<1.4	==	==	8
....	EXO	85/5/24	min	.02-2.5		4.	120.	8

Notes: (a) HEAO:HEAO-2 (Einstein Observatory) observations; EXO: EXOSAT observations. (b) Symbiotic phase: out = outburst; max = light maximum; min = light minimum, or quiescence; decl= decline phase after the outburst. (c) X-ray energy range in keV. (d) Fluxes in 10^{-13} erg cm^{-2} s^{-1} integrated for the given energy range. (e) Hydrogen column density in 10^{20} cm^{-2}. (f) Fluxes in 10^{-13} erg cm^{-2} s^{-1} corrected for the interstellar absorption.

References: (1) Willson et al. (1984). (2) Kwok and Leahy (1984). (3) Cassatella et al. (1985). (4) Anderson et al. (1981, 1982). (5) Cassatella et al. (1987). See Figure 11-34. (6) Jura and Helfand (1984). (7) Viotti et al. (1987). (8) Leahy and Taylor (1987).

fact that the result largely depends on the assumptions of the distance and the interstellar absorption. As discussed in the previous Section VIII, two of the three stars have a rather low reddening, with E(B-V) = 0.1 to 0.3 (see Table 11-7). But in the X-ray range, the dependence of the observed spectrum on the hydrogen column density is very high, also at low reddening values, and especially for the soft X-ray spectra like those of the symbiotic stars. Even more uncertain is the distance of these objects. The only case for which more than one HEAO-2 observation is available—HM Sge—the observed variation (see Table 11-9) is not much larger than the observational uncertainties. Taking into account other possible sources of variability (e.g., the stellar "activity" or the orbital motion, as discussed above for the variations observed in other wavelength ranges), the presence of a secular decay of the X-ray flux in these nova-like symbiotics is still a weak possibility.

IX.C. AG DRACONIS

The high-velocity star AG Dra was first observed with HEAO -2 on 11 April 1980 at a minimum luminosity phase of the star V~ 9.7). Anderson et al. (1981) reported the discovery of a strong X-ray flux of 2.1×10^{-12} erg cm^{-2} s^{-1} (in the energy range 0.2 to 1.0 keV). The spectrum appears soft and, if fitted with a bremsstrahlung spectrum, corresponds to a temperature of 1.1×10^{6}K and to an emission measure of EM=2.6×10^{55}cm^{-3} (Anderson et al. 1982). The integrated X-ray luminosity is then L_x(0.2-1.0 keV) = 5×10^{32} erg s^{-1}, for N(H)= 3×10^{20} cm^{-2}.

This star was observed again with the European EXOSAT satellite during 1985-86 by F.A. Cordova and R. Viotti and their collaborators. The first observation was made on 15 March 1985, a few weeks after a minor outburst of AG Dra, and the derived count rate was much lower than expected according to the rather large X-ray flux observed in April 1980 (see Cassatella et al., 1987). Within the EXOSAT accuracy, the X-ray source is point-like and centered on the star within the uncertainty of the EXOSAT satellite. The EXOSAT observations were repeated on 5 June and 5 November 1985, when AG Dra was again at minimum (V~9.8), and a larger X-ray flux was found, in much better agreement with the 1980 results. These EXOSAT observations show that the X-ray spectrum of AG Dra is very soft, with a temperature of about 3×10^{5}K (Piro et al., 1985; Cassatella et al., 1987). These two latter EXOSAT observations were made at two different phases (0.22 and 0.50) of the U-light curve discovered by Meinunger (1979), in order to search for any phase dependence of the X-ray flux and for a possible eclipse of the hot source at phase 0.5. The results, however, indicate no flux change between June and November 1985, and, therefore, do not support a U-phase dependence of the X-ray flux. In January 1986, AG Dra underwent a new outburst, and EXOSAT observations were repeated on February 14th when the star was still at near maximum luminosity. No X-ray flux was detected in spite of the large increase of the UV flux, as illustrated in Figure 11-34. At the same time, the UV spectrum showed only small variations, except for a large increase of the high-excitation HeII 1641 A line in 1986. The optical, ultraviolet, and X-ray observations of AG Dra during 1985-86 are shown in Figure 11-34.

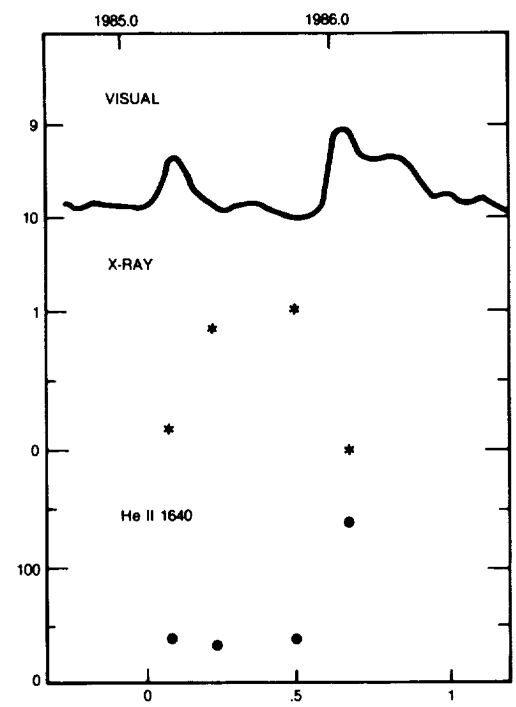


Figure 11-34. Optical, X-ray , and ultraviolet observations of AG Dra from March 1985 to Febraray 1986. From top to bottom: the visual light curve (Mattei, 1987), the EXOSAT X-ray flux (low enery, thin lexan filter; arbitrary units, and flux variation of the HeII 1640 A emission line.

It is clear that there exists a kind of anticorrelation of the X-ray emission with the stellar activity (where for "activity," we refer to the optical luminosity of the star). Furthermore, the X-ray fading was not followed by a simultaneous decrease of the emission line ionization, which is a frequent feature of symbiotic stars during outburst. However, also during the 1980 major outburst, no change of the ionization level of the UV emission line spectrum was noted (Viotti et al., 1984a).

IX.D. CH CYGNI

CH Cyg was detected as X-ray source with EXOSAT on 24 May 1985 by Leahy and Taylor (1987) when the star was in a phase of enhanced activity, characterized by a radio outburst and an increase of the ionization of the emission line spectrum, while the visual luminosity faded (Taylor et al., 1986). Previous observations with the HEAO-2 IPC detector gave only an upper limit, two orders of magnitude smaller than the EXOSAT flux (Leahy and Taylor, 1987, see their Table 2.11). There is an unidentified X-ray source in the HEAO-A2 experiment (Marshall et al., 1979) close to the position of CH Cyg, but, as discussed by Leahy and Taylor (1987), its identification with the symbiotic star is doubtful. Thus, the EXOSAT observations well probably represent the first X-ray detection of CH Cyg. This also implies that the star has largely increased its X-ray flux after the 1984 radio outburst, which puts it close to the small group of symbiotic novae, whose X-ray emission has been discussed above. From the analysis of the EXOSAT data, Leahy and Taylor concluded that the source is soft, with an integrated flux in the energy range 0.02-2.5 keV of about 1.3×10^{-11} erg cm^{-2} s^{-1}. As for the previous cases, we must consider that the derived fluxes critically depend on the assumed hydrogen column density and on the model used to fit the observational data. In particular, in the case of CH Cyg, the value $N(H)=4\times10^{20}$ cm^{-2} adopted by Leahy and Taylor is probably too high in comparison with the much lower column density that can be derived from the interstellar Lyα absorption, as discussed in their Section 2.6.2 (see their Table 2-8). Finally, EXOSAT observations seem to indicate a possible short-time variability during the 15 minutes of observations with the Thin Lexan filter of the LE1 telescope, with a time scale of the order of 5 minutes. If confirmed, this value, close to the flickering time scale of 5 to 7 minutes found by Slovak and Africano (1978) could support a model of X-ray emission from an inner boundary layer of an accretion disk (Leahy and Taylor, 1987). We shall come back to this problem in the following Chapter 12.

IX.E. R AQUARII

R Aqr is the second of the two symbiotic stars first detected in X-rays with EXOSAT. This is a Mira variable with a symbiotic spectrum and several other peculiarities, such as the anomalies of the Mira light curve, the strong radio emission and the radio jet-like features, the small planetary nebula around it, and the rich emission line spectrum. All these features will be discussed in details in Chapter 13, Section V. The many peculiarities and the relative vicinity (about 300 pc) make R Aqr an obvious target for X-ray satellites. The star was, in fact, observed with HEAO-2 on 1 June 1979, using the High Resolution Imagery (HRI), and on 21 June 1980, using IPC. In both cases, R Aqr was close to the minimum of its Mira light curve (about V=10). While there was no detection in the HRI image of June 1979 (Seward, 1985), a "marginal" flux was measured by Jura and Helfand (1984) from the more sensitive IPC observation of June 1980. However, a reanalysis of the original HEAO-2 observations using an improved data processing software available at the Center for Astrophysics of Cambridge, led Viotti et al. (1986b, 1987) to conclude that there is no evidence in the June 1980 IPC image of any X-ray source at the position of R Aqr. The estimated count rate upper limit was 0.010 s^{-1} for the broad (0.2-3.5 keV) energy range of IPC. The disagreement between Viotti et al. and Jura and Helfand again should be attributed to the different ways these data can be treated and the dependence of the results on the techniques, especially in the case of low fluxes as in the case of R Aqr. One should also consider that Jura and Helfand (1984) also derived a marginal flux for the prototype of the Mira variables o Ceti, which should be a crucial result for understanding the nonthermal processes in Mira variables. However, also in this case it should be considered only as an upper limit, rather than a real detection (Seward, 1985).

R Aqr was observed with EXOSAT on June 14 and December 24, 1985, during two different phases (0 and 0.5) of the Mira light curve, and a weak flux was detected with the LE1 detector equipped with a Thin Lexan filter, Viotti et al. (1987) measured a background corrected count rate of 5.4 and 4.6×10^{-3} s^{-1} for the June and December 1985 observations, respectively. Within the errors, the count rates at the two epochs are the same, in spite of the large change of the visual magnitude of the Mira (V = 6.1 and 8.2, according to the IUE FES, Viotti et al., 1987). Therefore, the observed X-ray emission is not directly related to the pulsation of the Mira giant. Assuming a low reddening (logN(H)=20.2) and a soft X-ray spectrum ($T = 2\text{-}3 \times 10^5$K), Viotti et al. derived an X-ray flux of about 2×10^{-11} erg cm^{-2} s^{-1} in the 0.2-1 keV range. At a distance of 300 pc, the X-ray luminosity is 1×10^{30} erg s^{-1}. This value is close to the HEAO-2 upper limit reported above, and implies that at least the X-ray flux did not decrease between 1980 and 1985. Figure 11-33 shows the X-ray EXOSAT map of R Aqr. The source is point-like within the errors, but there is in both the June and December 1985 images an indication of an elongation of the image in the NE-SW direction, nearly the same as the orientation of the radio "ejecta" discussed by Hollis et al. (1986). Viotti et al. (1987) discussed these observations and, also on the basis of the IUE observations showing the high-temperature lines of NV and HeII in the spectrum of the jet stronger than in the spectrum of the central star, concluded that X-rays are mostly emitted from the jet. Clearly, high spatial resolution X-ray imagery is needed to better clarify this point.

X. SUMMARY OF THE OBSERVATIONS

X.A. THE SYMBIOTIC PHENOMENON

The symbiotic stars enbody features that are typical of many different categories of astrophysical objects: planetary nebulae, bipolar nebulae and jets, cocoon objects, ζ Aur and VV Cep stars, Mira and OH-IR variables, peculiar Be stars, novae, and cataclysmic variables. In addition, there is evidence for phenomena possibly associated with physical processes such as stellar winds, mass transfer and accretion, disks and streams, thermonuclear outbursts, dust condensation, and shocks. These are the many aspects of *the symbiotic phenomenon*. It should be clear to the reader, at this point, that the study of the symbiotic phenomenon can have a great impact on the understanding of a large amount of phenomena, which are relevant to many different classes of astrophysical objects. To proceed in our investigation, we have first to put the above described variety of information in a quantitative scheme and to determine the physical properties of our targets. In particular, we have to find a basis, a "counter stone" for our picture, and to provide a simplified scheme of the time behavior of the different phenomena. We shall try to do this in the following sections.

X.B THE COOL COMPONENT

The energy distribution of symbiotic stars typically presents three spectral components (e.g., Boyarchuk, 1969). The UV-to-IR spectrum of the S-type symbiotic BF Cyg is shown in Figure 11-35a. It is evident that for this star the visual range is a minimum of the energy spectrum.

As discussed above, in symbiotic stars, the cool spectral component is the most common feature, which generally leaves little doubt about its origin. This belief is based on the energy distribution showing, in most cases, a maximum in the

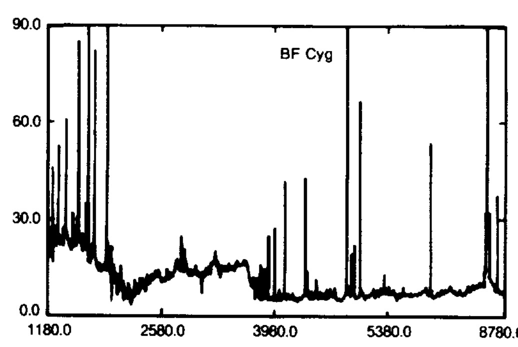


Figure 11.35a. The ultraviolet-to-infrared energy distribution of the symbiotic star BF Cyg (Cassatella et al., 1988b).

red-near IR, and on the presence of "photospheric" absorption lines and bands, especially in S-type symbiotics. It has been argued that the TiO bands and the absorption features could be formed in an outer cool absorbing layer like in the Mira variables, rather than in a stellar atmosphere. However, as already discussed in the previous section, this hypothesis is hard to maintain. Therefore, the cool component is the only characteristic of a symbiotic object that could be directly related to a "normal" stellar atmosphere. In the visible, the spectrum of a symbiotic star appears "peculiar" (See Figure 11-35b), but if our eyes and our instrumentation were sensitive only to the near-IR range, i.e., between 7000-8000 A and 1-2 µm, we would find, in most cases, a normal M-type spectrum with small amplitude irregular variations (in S-type systems), or with periodic Mira-type oscillations (for the D-type ones). Perhaps we might see some emission lines, especially in the latter objects, but this would be considered not unexpected because of the presence of a pulsating star. Certainly, we should not have the need to introduce a second star. The situation changes as soon as we move beyond the near-IR region, where the "peculiarities' emerge, and this is the case of the visual.

Let us better clarify this important point. For any scientific investigation, we have to decide about the best starting point. This should possibly be a well-established physical property of our phenomenon. In the case of the symbiotic stars, the classical approach is first to describe their behavior in the visual, but as shown in this chapter, for most objects, this is very confusing and difficult to put into a coherent picture. On the other hand, the near-IR is much simpler: in the S-type symbiotics, the cool spectral component is represented by a normal late-type photospheric

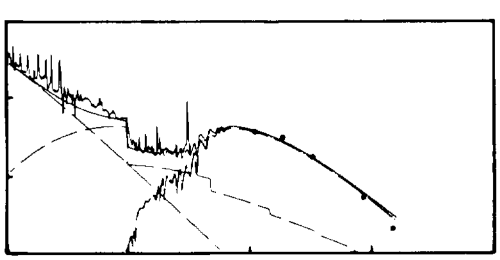


Figure 11.35b. Preliminary model of the energy distribution of BF Cyg. The main spectral components are included (Cassatella et al., 1988b).

spectrum. IR monitoring has disclosed the presence of irregular, small amplitude variations, (generally uncorrelated with optical and UV "activity"), which are not unusual among the majority of the "nonsymbiotic" late-type giants and supergiants.

Let us thus make the following statements: (1) the cool spectral component of the S-type symbiotics is a *cool star*, and (2) it behaves (near the maximum of its energy spectrum) like a *normal* cool star.

In the case of the (fewer) D-type symbiotics, there is no doubt about the presence of Mira-type periodicity, with a somewhat irregular light curve and possible secular trends, for all those objects which have been studied in the IR for long enough. Their light curves are rather irregular, which is, however, a common feature of the light curves of the "normal" Miras. The amplitude of the variations in J and K is, in general, rather large (up to about one magnitude) in fair agreement with the amplitudes observed in "normal" Miras (see Feast et al., 1982). This implies that most of the radiation in the 1-3 µm range comes from the cool variable source, while other possible contributors, especially emission from circumstellar dust, are less important. There is the problem of the difficulty of detecting the spectral features associated with a Mira star, such as the TiO bands in the visual. This could be explained by the small contribution of the cool component continuum to the visual region because of the dominant hot continuum. However, this molecula has been clearly identified in the classical D-type symbiotic RR Tel at 8206 A and elsewhere (Thackeray, 1977; note added in proofs). As discussed in Section VI.B. steam absorption bands have been observed in the IR of this star near 3 µm, where the cool spectrum dominates.

Again, we are brought to the conclusion, which is probably less firm than in the previous case of the S-type symbiotics, that also for the D-type symbiotics, the cool spectral component is *a cool star that is a Mira variable*. Therefore, following the suggestion of Whitelock (1988), it would be more appropriate to call them *symbiotic Miras* or *Mira-type symbiotic stars*. However, we have to recall that we are considering here only those stars for which there are enough infrared observations, and not all those objects that are included in the list of D-type symbiotics.

Now we have a good starting point for our study (1).

The next step would be to assume that these cool stellar components of the symbiotic systems have the same bolometric luminosity as the "nonsymbiotic' cool stars with the same spectral features. So far, there is no evidence against this assumption. But if the peculiarity of the symbiotic stars were associated with a higher chromospheric/coronal activity of the cool star, it would be possible that the enhanced activity would affect the relationship between bolometric magnitude and spectral type and luminosity class. However, so far, we have little ability to probe the chromospheric activity of the cool star, because it is very difficult to separate the stellar chromospheric spectral features from those originating in the hot circumstellar environment or nebula, or in the same cool star's atmosphere heated by the hot source's radiation. Probably, high resolution, high S/N spectrophotometry of some emission and photospheric absorption lines during the whole cycle of variability of a symbiotic star, should provide clear information about the place where the lines are formed and about the structure of the cool star's atmosphere and, eventually, about the presence and extension of a chromosphere. Fourier Transform Spectroscopy (FTS) observations in the near-IR would be of particular relevance for the problem. At this stage, the comparison of the apparent (dereddened) luminosity of the cool stellar component of a symbiotic star with the bolometric luminosity of a normal cool star seems to be the best and the most correct way we have to derive the distance of a symbiotic star.

D-type symbiotics are thought to be surrounded by extensive dust envelopes that are heated by the stellar radiation(s). It is also possible that the cool star is somewhat or largely obscured by the circumstellar dust, for instance, as suggested by Kenyon et al. (1986). So the apparent luminosity of the Mira could be underestimated, and the distance overestimated. For instance, Rossi et al. (1988) derived for the D-type southern symbiotic BI Cru a distance of 3800 pc. This value should be reduced by a factor of about 2 in the case of the presence of a thick dust envelope around the Mira component. This fact and the larger uncertainty in the absolute magnitude of the field Miras make the determination of the distances of the D-type symbiotics more uncertain than those of the S-type ones. Table 11-10 gives the spectral types of the cool components of symbiotic stars. Once the spectral type is known, the distance can be derived from the K-magnitude (if not variable) and from A_k, the interstellar extinction at 2.2 μm ($A_k = 0.112 x A_v = 0.346 x E(B-V)$, e.g., Rieke and Lebofsky, 1985), assuming for the cool star the same absolute K-magnitude of a non-emission line, non-variable star with the same spectral type and luminosity class. The reddening of the symbiotic stars was discussed in Section VIII.B. Table 11-11 summarizes the reddening and distance estimates for many symbiotic stars.

X.C. VARIABILITY

The second main distinguishing feature of the symbiotic phenomenon is the photometric and spectroscopic variability in all the frequency ranges. From the previous discussions, it appears quite hard to give a consistent picture of the observed variability, for both the large differences from star to star and for the changes between different phases in the same star. In general, we can state that variations are: (1) very irregular, (2) the dominant variation is on a long time scale (several months to years), and (iii) the amplitude of the long time scale variation is of the order of one to a few magnitudes, and is larger towards smaller wavelengths. In addition, periodic variations have been observed in a number of objects, and the associated periods are of the order of several hundred days. Short (days) or very short (minutes or seconds) time scale variations are also present, but so far they have not been investigated enough.

The symbiotic phenomenon is, therefore, mainly characterized by the long and irregular photometric variability. The behavior is not the same in different spectral regions. In particular, as described above, in the IR, a Mira-type vari-

(1) However, we should consider that the above "paradigma" that there is a cool star inside a symbiotic system needs to be checked "a posteriori" for each individual star. In particular we must verify whether the cool stellar components are placed in the H-R diagram in the same place as the normal cool giants and supergiants.

TABLE 11-10. SPECTRAL TYPES OF THE COOL COMPONENTS OF SYMBIOTIC STARS.

Star	IR Type	Spectrum			Remarks	Ref.
Z And	S	M	3.5	III		1
EG And	S	M	2.4	III		1
R Aqr	S	M	7	III	Mira	1
UV Aur	S	N			carbon star	2
TX CVn	S	K	5.3	III		1
T CrB	S	M	4.1	III	recurrent nova	1
BF Cyg	S	M	5	III		1
CH Cyg	S	M	6.5	III	radio-active	1
CI Cyg	S	M	4.9	II		1
AG Dra	S	K	3	III		3
YY Her	S	M	3.0	III		1
V443 Her	S	M	5.1	III		1
RW Hya	S	M	1.1	III		1
BX Mon	S	M	4.6	III	(Mira)	1,4
SY Mus	S	M	4			5
RS Oph	S	K	5.7	I-II	recurrent nova	1
AR Pav	S	M	3-4	II-III		1
AG Peg	S	M	3.0	III	symbiotic nova	1,5
AX Per	S	M	5.2	II-III		1
RT Ser	S	M	5.5		symbiotic nova	1
PU Vul	S	M	4-5		symbiotic nova	1
LMC S63	S	R			carbon star	6
BI Cru	D	M			Mira	7
V1016 Cyg	D	>	M4		Mira, symbiotic nova	1
V1329 Cyg	D	>	M4		symbiotic nova	1
RX Pup	D	>	M5		Mira	5
HM Sge	D	>	M4		Mira, symbiotic nova	1
RR Tel	D	>	M5		Mira, symbiotic nova	5
He 2-38	D	>	M5			5
M1-2	D'	G	2			8
HD 149427	D'	F				9
HD 330036	D'	F	5	III-IV		10

Notes: (a) S, D, D' infrared types as from Allen (1982). (b) Mira: Mira-type IR variability (e.g., Whitelock, 1987). Recurrent nova: see Kenyon (1986). Symbiotic nova: see Viotti (1988b).

References: (1) Kenyon and Fernandez-Castro (1987). (2) Nassau and Blanco (1954). (3) Viotti et al. (1983). (4) Viotti et al. (1986). (5) Schulte-Ladbeck (1988). (6) Allen (1979). (7) See discussion of Rossi et al. (1988). (8) O'Dell (1966). (9) Webster (1966). (10) Lutz (1984); see also Webster (1966).

ability was discovered in all the D-type symbiotics that were observed for long enough time. In some cases, the Mira pulsations have also been found in the visual, although with a much smaller amplitude and during quiescence. But the main photometric characteristics of the visual variability are the nova-like brightenings of the symbiotic novae, such as RR Tel, and the recurrent, but not clearly periodic, long-term oscillations like those observed in Z And. The first type of behavior is clearly to be associated with some kind of "Cataclysma," whose repetition time--if the event is recurrent--should be very long (>> $10\text{-}10^2$ y).While the Z And-type quasi-periodic oscillations could be related to a softer and repetitive process, such as stellar surface activity, pulsation, instability of an accretion disk or stream, etc., or to the orbital motion of a binary system, or to both. In between the RR Tel-type variability and the Z And-type one, there is a large range of different behaviors, as described in the previous sections, which are hard to classify, unless more information is available on the individual objects.

X.D. BINARITY AND ORBITAL GEOMETRY

The next step of our study is to determine whether the symbiotic phenomenon is associated with the presence of a close interacting binary system. First, we have to find out if we are dealing with two stars. Then, if the system is subject to strong gravitational and radiative interactions, and to mass exchange, or at least if the binarity has or has had at least partly a fundamental role in the present atmospheric structure of each component, for instance, on their chromospheric/coronal activity. In fact, even if the stars were at present far enough to not strongly interact, their physical properties (e.g., rotation) could have been influenced by the earlier evolutionary stages of the system, when the stars were closer. Thus in any case binarity is an important parameter to be determined in symbiotic objects.

For visually unresolved double star systems, the classical criteria of binarity are: periodic variations in the radial velocity curve of the photospheric lines (spectroscopic binaries) and periodic light variations associated with partial or total eclipses of one star by the other and with reflection effects (Leibowitz and Formiggini 1988). Both criteria work if the orbital plane is not too inclined with respect to the line of sight. Thus, even if all the symbiotic objects were binaries, we should expect to directly identify the binarity only for some of them. There are statistical means to estimate the "a priori" fraction of positive detections, but these computations are based on some assumptions about the orbital parameters and the stellar sizes that are rather uncertain. Conversely, there are other "indirect" ways to decide about binarity, which will be discussed later.

Periodic variation of the radial velocity of the photospheric lines of the cool star, possibly associated with phase-shifted luminosity variation, appears the best criterion of binarity. As discussed in Section IV.E, Garcia (1986, see also Garcia and Kenyon, 1988) has found periodic cool-component radial velocity variations in several S-type symbiotics. These results are generally in agreement with long-period photometric variability, and strongly support their binary nature. Two notable exceptions are Z And and RW Hya, whose photometric and spectroscopic curves have not the expected phase difference. This suggests rather complex geometric effects (Garcia and Kenyon, 1988).

Let us now discuss the long-time scale light oscillations found in different wavelength regions. There is no doubt that the large IR variations found in D-type symbiotics are associated with a pulsating star, rather than with eclipses. The latter hypothesis must be excluded, especially because of the large size of the eclipsed object, if it is a cool giant. Small amplitude long-term variations have been found in several symbiotic stars belonging to both types. These variations are generally seen during a quiescent phase of the symbiotic object, but still could be a residual of the symbiotic activity that is characterized by time scales of the same order. This might also be suggested by the associated spectral variability, such as the long term Hα (Altamore et al., 1979) and UV variations (Fernandez-Castro et al., 1988). However, these photometric (and associated spectroscopic) long-term variations of symbiotic stars could simply be explained by periodic eclipses or reflection effects in a binary system; and the discovery of periodic radial velocity changes in many symbiotics makes this interpretation the most plausible, for these systems at least.

Given the period and the radial velocity curve,

TABLE 11-11. ORBITAL PARAMETERS OF SYMBIOTIC SYSTEMS.

Object		T (a)	Vo (b)	K (c)	e (d)	Ref
Z	And	750	+2	8.1	(0.0)	1
EG	And	482	-95	5.1	0.17	2
....		492	-94	7.1	(0.0)	1
UV	Aur	388	+6	5.1	(0.0)	1
TX	CVn	199	+2	6.1	0.2	1
CH	Cyg	5700:	-58	4.9	0.47	3
CI	Cyg	812	+18	6.5	(0.0)	1
AG	Dra	530	-146	5.3	(0.0)	1
RW	Hya	366	+14	8.7	(0.0)	1
AG	Peg	819	-16	5.0	0.28	4
....		796	-14	6.4	(0.0)	1
AX	Per	601	-114	6.7	(0.0)	1

Notes to the table.

(a) Orbital period. (b) Radial velocity of the system (in km s^{-1}). (c) Half amplitude of the radial velocity curve (in km s^{-1}). (d) Eccentricity. Garcia and Kenyon (1988) found, for most of their stars, not enough data to justify fitting with an eccentric orbit.

References: (1) Garcia and Kenyon (1988). (2) Skopal et al. (1988). (3) Mikolajewski et al. (1988). (4) Slovak et al. (1988).

it is possible to infer some basic parameters of the binary system. Table 11-11 gives the orbital elements of some symbiotic systems. The corresponding mass functions are in the range 0.003 to 0.042 M (Garcia and Kenyon, 1988). Note that there is a number of cases where a significant eccentricity of the orbit seems to be present. Although the orbital constants need to be confirmed, there is now a fairly convincing ground that most symbiotic objects—especially the S-type ones—are wide binary systems.

X.E. STATISTICAL CONSIDERATIONS

When one deals with a group of objects showing a certain number of common characteristics as in the case of the symbiotic stars, two main questions have to be posed: (1) Do they constitute a homogeneuos group of objects so that we can speak of symbiotic stars as a whole? That is, do they represent a well-defined stage of the stellar evolution? (2) Which are the mean physical parameters defining this group?

As already discussed in the previous sections, symbiotic stars do not seem to represent a homogeneous stellar group, unless we restrict ourselves on some smaller samples, such as the symbiotic novae. Moreover, for most of the objects so far classified as symbiotic, the available information is not sufficient to define their nature to some extent. We, therefore, shall restrict our discussion to a comparison of the symbiotic objects with other categories of astrophysical objects. Most of the classification criteria are based on the optical multicolor photometry. But in the case of symbiotic stars the broad-band magnitudes are strongly affected by the emission lines, whose strength and relative intensity are largely variable from star to star and from epoch to epoch for the same star. In the near-IR, the emission lines are generally weaker with respect to the continuum. Thus, the IR photometry may provide some more physical information. The color-color diagrams in the near and far (=IRAS) infrared (e.g., Allen 1982; Whitelock, 1987, 1988; Kenyon et al., 1988) permit one to separate the symbiotic objects into at least two categories: those falling in the region of the late-type giants, and those spread out on a more extended region generally occupied by the Mira variables, the

TABLE 11-12. BASIC DATA ON SYMBIOTIC STARS AND RELATED OBJECTS (*).

Object	l	b	IR	Spectrum	V	K	E(B-V)	Dist.
	(1)		(2)	(3)	(4)	(5)	(6)	(7)
Z And	110	0	S	M3.5III	10.8	5.0	0.35	1.12
EG And	122	-22	S	M2.4III	7.5	2.6	0.07	0.63
AE Ara	344	-9	S	M 2	12.5	6.3		
UV Aur	174	-23	S	N	7.9	2.1		
BI Cru	300	0	D	M	12.3v	4.8v	1.5	3.8
BF Cyg	63	7	S	M 5 III	12.3	6.3	0.49	
CH Cyg	82	16	S	M6.5III	8.2	-0.7	0.02	
CI CYG	71	5	S	M4.9 II	11.0	4.5	0.40	
V1016 Cyg	75	6	D	> M 4	10.5	4.5v	0.28	
V1329 Cyg	78	-5	S	> M 4	13.7	6.8v	0.37	
AG Dra	10	41	S	K 3 III	9.9	6.2	0.06	0.70
YY Her	48	17	S	M3.0III	13.6	8.0	0.18	
RW Hya	315	36	S	M1.1III	10.	4.7	0.03	
BX Mon	220	6	S	M4.6III	11.9	5.7	0.20	2.80
SY Mus	295	-4	S	M2	11.2	4.7	0.40	
AR Pav	328	-22	S	M3-4II/III	11.	7.2	0.30	
AG Peg	69	-31	S	M3.0III	8.6	3.6	0.12	0.50
AX Per	130	-8	S	M5.2II/III	11.9	5.5	0.29	2.82
RX Pup	259	-4	D	> M 5	10.9	2.0v	0.7	1.0
HM Sge	54	-3	D	> M 4	10.7	3.6v	0.5	1.0
RR Tel	342	-32	D	> M 5	10.5	4.1v	0.10	
PU Vul	63	-9	S	M4-5III	8.8	5.9	0.49	
LMC S63	--	--	S	R	14.7	11.3	<0.02	55.0
Related Objects								
R Aqr	67	-70	S	M 7 III	6-11	-1.0V	<0.10	0.30
T CrB	42	48	S	M4.1III	10.2	4.8	0.15	1.43
RS Oph	20	10	S	K5-7 I-II	11.4	6.5	0.6	
RT Ser	14	10	S	M5.5	13.	7.0		

Notes to the table:

(*) Data collected mostly from Allen (1982, 1984), Kenyon (1986) and Mueller and Nussbaumer (1988). For individual objects: BI Cru: Rossi et al. (1988); BX Mon: Viotti et al. (1986); RX Pup: Allen and Wright (1988); LMC S63: Kafatos et al. (1983).

(1) Galactic coordinates (Allen, 1984).

(2) IR type (Allen, 1982).

(3) Spectral type of the cool component (Table 11-10).

(4) Visual magnitude at min (for S-type symbiotics) or after outburst (for D-type symbiotics). In many cases, the magnitudes are derived from the data published by the AAVSO bulletins (Mattei, 2988).

(5) K-magnitude (maximum value if variable).

(6) Interstellar colour excess (Table 11-7).

(7) Distance (in kpc).

OH-IR masers, and the compact planetary nebulae.

Emission line intensities, especially in the ultraviolet spectra, generally suggest line formation in rather dense (10^6-10^{10} cm^{-3}) regions, denser than in the classical planetary and gaseous nebulae. Schwarz (1988) applied to the symbiotic stars the classification method of Baldwin et al. (1981), which is based on the [OIII] 5007/Hβ and [OII] 3727/[OIII] 5007 line ratios. In the diagram 5007/4861 against 3727/5007, planetary nebulae and HII regions occupy two well-defined regions. Schwarz found that most symbiotic stars (both S, and D-D'-types) are spread out in the diagram, but the D, D' types are closer to the planetary nebulae region.

A different approach can be made by using the radial velocities (and proper motion if available), together with the galactic coordinates. Wallerstein (1981) first noted that the radial velocity dispersion of the (few) symbiotic stars in his sample is rather high (63±14 km s^{-1}, averaged on 19 objects). This value remains high even if the peculiar high-velocity star AG Dra is not included.

The galactic distribution (Figure 11-36) shows a fairly strong concentration towards the galactic plane and the galactic center, and suggests an old disk population (Boyarchuck, 1975; Wallerstein, 1981; Kenyon, 1986). This conclusion, however, should be taken with some care. For instance one should consider that one of the most representative symbiotic objects, AG Dra, for its high-velocity and high-galactic latitude, is clearly a halo object.

An ultraviolet color-color (C1, C2) diagram was recently proposed by Kenyon and Webbink (1984). This diagram is based on the UV fluxes near four continuum regions (1300 A, 1700 A, 2200 A, and 2600 A), and is useful as diagnostics of the hot and nebular components (which, as discussed in Section VIII.C, generally dominate the SW and LW spectral regions of IUE, respectively), and eventually the accretion rate. The

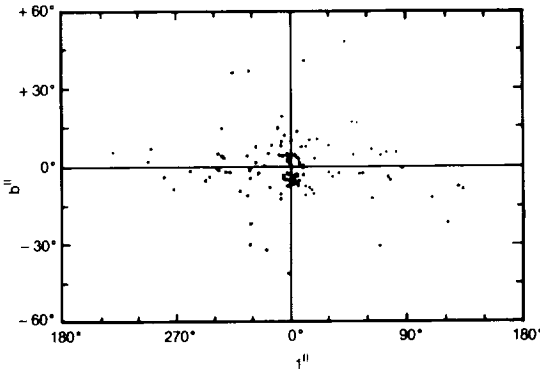


Figure 11-36. Distribution of symbiotic stars in galactic coordinates (Kenyon, 1976).

comparison of the observed colors with computed trajectories (Figure 11.37) seems to suggest that symbiotic stars possess either accreting main-sequence stars, or hot stellar sources (Kenyon and Webbink, 1984; Kenyon 1986).

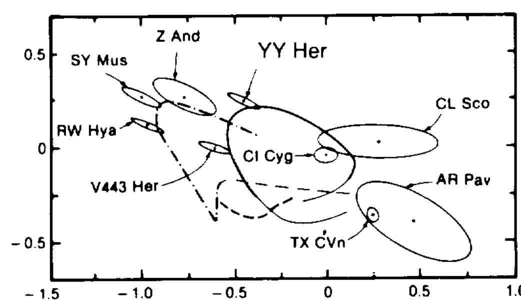


Figure 11-37. The C1-C2 diagram for symbiotic stars (Kenyon and Webbink, 1984; Kenyon, 1986).

The problem of the classification of symbiotic stars is still open. But the above examples illustrate the need for new methods of statistical analysis (not only for the symbiotic stars), and the need to focus on those observational parameters that can provide information on which process is going on. The previous Table 11-12 summarizes the basis observational data on the symbiotic stars.